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INSTALLATION OF FLEXIBLE MEMBRANE LINING IN MT. ELBERT FOREBAY RESERVOIR

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16. ABSTRACT

During the summer of 1980, the USBR (Bureau of Reclamation) installed 117 ha (290 acres) of 1.14-mm (45-mil) CPER (reinforced chlorinated polyethylene) flexible membrane lining in the Mt. Elbert Forebay Reservoir, near Leadville, Colo. The forebay reservoir and adjacent Mt. Elbert Pumped-Storage Powerplant are part of the East Slope Power System of the Fryingpan-Arkansas Project. The installation at Mt. Elbert constitutes the world's largest single-cell flexible membrane lining application to date, and is the first time that such a material has been used in a pumped-storage reservoir for seepage control. To meet the USBR requirement for power online for the powerplant by July 15, 1981, the installation had to be accomplished in one construction season. This would allow sufficient time to fill the reservoir and conduct acceptance tests on the generating units and accessory equipment. Summarized in this report are the construction work associated with the installation of the membrane lining, the Quality Assurance Program conducted during the installation, and the research program being implemented to monitor the performance of the lining.

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Applied Sciences Branch
Division of Research
and
Embankment Dams Section
Dams Branch
Division of Design
Engineering and Research Center
Denver, Colorado

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UNITED STATES DEPARTMENT OF THE INTERIOR ★ BUREAU OF RECLAMATION

ACKNOWLEDGMENTS

The membrane installation was accomplished under the direction of Bureau of Reclamation personnel William Fraser, Project Construction Engineer, Salida, Colo.; and William McCormick, Field Engineer, Twin Lakes, Colo. Principal designer for this work was Edward Gray, Jr., Embankment Dam Specialist, Division of Design, E&R Center, Denver. The laboratory acceptance program was developed by R. K. Frobel and W. R. Morrison, and was conducted by L. D. Casson, J. J. Swihart, and G. J. Myers, under the direction of J. L. Kiewit, Head, Materials Science Section, and L. O. Timblin, Jr., Chief, Applied Sciences Branch, Division of Research, E&R Center, Denver. Inspection of the fabrication plants was conducted by Bureau Resident Inspectors Robert Oksanen and T. R. Enright, under the direction of P. R. Walters, Head, Inspection Section, and T. F. Simms, Chief, Equipment Installation and Inspection Branch, Division of Construction, E&R Center, Denver. Field inspection was conducted by Bureau personnel D. Paul, J. Shisler, R. Benik, R. McGovern, M. Bliss, A. Weeks, P. Hoffman, and R. Inman, under the direction of W. Pierson, Supervisory Civil Engineer. Technical assistance provided by Watersaver Company, Inc., Staff Industries, Burke Rubber Company, Dow Chemical Company, J. P. Stevens Company, Schlegel Lining Technology, Inc., and the B. F. Goodrich Company is appreciated. The engineers who authored this publication wish to express a special thanks to the Word Processing, and Publications Planning and Graphics Units. Final editing and preparation of the manuscript for publication was performed by C. H. Rich, Technical Publications Branch.

CONTENTS

TABLES

FIGURES

CONTENTS—Continued

INTRODUCTION

General

During the summer of 1980, the USBR (Bureau of Reclamation) installed approximately 117 ha (290 acres) of 1.14-mm (45-mil) CPER (reinforced chlorinated polyethylene) flexible membrane lining in the Mt. Elbert Forebay Reservoir. The reservoir, for the Mt. Elbert pumped-storage facility, is situated uphill approximately 1036 m (3400 ft) north of Twin Lakes. These lakes are a pair of glacial-age lakes located in Lake County approximately 24 km (15 mi) southwest of Leadville, Colo. Located at an elevation of 2940 m (9645 ft), the forebay reservoir is approximately 133 m (435 ft) above the Mt. Elbert Pumped-Storage Powerplant. The forebay reservoir and the Mt. Elbert Pumped-Storage Powerplant are part of the East Slope Power System of the Fryingpan-Arkansas Project.

Most of the water used for power generation must be pumped into the forebay reservoir from Twin Lakes. Additional water for power production comes from the western slope of the continental divide. The North Side and South Side Collection Systems on the western slope collect runoff from snowmelt above 3048 m (10 000 ft). The water is brought to the eastern slope via tunnel to Turquoise Reservoir where it is held in temporary storage until conveyed through the 16.6-km (10.3-mi) long Mt. Elbert conduit to the forebay reservoir.

The reservoir can impound 14.22×10^6 m^3 (11 530 acre-ft) of water of which 8.8×10^6 m^3 (7160 acre-ft) are available to develop 200 MW (268,000 hp) of electrical power during peak demand. Two 103-MW (138 000-hp) hydroelectric turbine-generators will generate the power. These generators are also designed to operate as 127-MW (170 000-hp) motors to drive the turbines in reverse to pump the water from Twin Lakes back to the forebay reservoir during nonpeak hours.

The CPER installation at Mt. Elbert constitutes the world's largest single-cell flexible membrane lining application to date, and is the first time that such a material has been used in a pumped-storage reservoir for seepage control. To meet the USBR requirement for power online for the powerplant by July 15, 1981, the installation had to be accomplished in one construction season. This would allow sufficient time to fill the reservoir and conduct acceptance tests on the generating units and accessory equipment.

The membrane lining was installed under USBR Specifications No. DC-7418 [1].[1] Green Construction Company of Des Moines, Iowa, was awarded the contract on April 16, 1980, and installation was completed on September 20, 1980.

The B. F. Goodrich Company of Akron, Ohio, was the subcontractor who furnished and installed the membrane lining. The cost of the work is summarized below:

Item	Engineer's estimate	Bid price
Total	\$20,566,000	\$17,884,170
Furnish and install membrane lining	\$10,160,000 (\$8.61/m^2) (\$0.80/ft^2)	\$ 8,712,200 (\$7.38/m^2) (\$0.686/ft^2)

This report summarizes the construction work associated with the installation of the membrane lining, the QA (Quality Assurance) Program conducted during the installation, and the research program being implemented to monitor the performance of the lining. A design summary prepared in the Division of Design [2] contains the concepts used in the preparation of the specifications for the membrane liner.

Background Information

Figures 1 and 2 are plan and detail drawings of the reservoir, respectively. Figure 3 is an aerial photograph of the forebay reservoir taken during the early stages of construction.

The forebay reservoir has a surface area of 117 ha (290 acres) at an elevation of 2940 m (9645 ft), the top of active conservation capacity. The minimum operational water surface is at an elevation of 2931 m (9615 ft) The reservoir is located above the glacier-scoured valley now occupied by Twin Lakes Reservoir, in a topographic depression bordered on two sides by ridges of glacial debris and on a third side by an alluvial fan. The reservoir was built under contract from 1975 to 1977 by constructing a small dike in the open southwest corner of the depression and a 27-m (90-ft) high zoned earth embankment across the open north side. A portion of the hillside between the forebay reservoir

[1]The numbers in brackets refer to items in the Bibliography.

and the lower lake had been geologically mapped as an ancient landslide. Considerable concern has been expressed that seepage from the reservoir might reactivate the slide.

The concern over seepage and its effects on the hillside resulted in a decision to completely line the reservoir with an impervious material. Although several alternatives were considered, a 1.5-m (5-ft) normal thickness of reservoir lining consisting of zone 1 earth material was decided upon. Zone 1 material consists of a collective mixture of clay, silt, sand, and gravel originally compacted in 150-mm (6-in) lifts with tamping rollers. The depression was reshaped to provide a bottom shape suitable for placement of the 1.5-m (5-ft) thick earth liner. The earth lining was placed over the entire reservoir area up to an elevation of 0.9 m (3 ft) above maximum water surface. The lining placement was completed in the fall of 1976 and the main embankment was completed in 1977.

Permeability testing of the earth lining materials was performed in 1977 and 1978. Laboratory permeability studies were performed on earth material retained from 86 record tests from the original lining placement. Permeability rates from 15 tests were in excess of 1.0×10^{-8} m/s (1 ft/yr) but less than 9.7×10^{-7} m/s (100 ft/yr). As a result, 20 shallow well permeameter tests were performed on the inplace lining. Fifteen tests indicated that the lining was semipervious (permeabilities between 1.0×10^{-8} and 9.7×10^{-7} m/s (1 and 100 ft/yr)). Also, five large-scale ring permeameter tests were performed on the lining and three of these indicated semipervious material.

The laboratory and field tests on the earth lining materials and the inplace earth lining, respectively, indicated that the permeability of the earth lining was higher than anticipated. The field testing indicated that the permeability of the inplace lining was probably 1.0 to 2.9×10^{-8} m/s (1 to 3 ft/yr). In the laboratory the permeability was influenced significantly by density. A minimum density equal to 100 percent of standard Proctor maximum dry density was generally needed to produce a permeability of 1.0×10^{-8} m/s (1 ft/yr) or less. The decision was made, therefore, that the reservoir lining would be rerolled to ensure an inplace density equal to or greater than Proctor maximum in the top 0.46 m (18 in).

The rerolling was accomplished during the fall of 1977 and spring of 1978 under change orders to Specifications No. 70-C0032 [3]. Prior to rerolling, inplace density tests indicated an average inplace density of 95.2 percent of Proctor maximum density. After rerolling, the average inplace density from 275 tests was 103.9 percent.

Five large-scale ring permeameter tests in the rerolled earth lining indicated an average inplace permeability of approximately 0.9×10^{-8} m/s (0.9 ft/yr). Thus, the rerolling did reduce the inplace permeability in the top 0.45 m (18 in) to the required value.

Between November 1977 and March 1978, water was pumped from the lower lake into the eastern half of the forebay reservoir. A low earth dike constructed approximately in the center of the reservoir prevented water from filling the western half of the reservoir. The water was introduced in stages until a depth of approximately 7.6 m (25 ft) (elevation 2926 m (9600 ft)) was reached. The water level remained at or slightly below this elevation until September 1979. The reservoir was then drained in anticipation of installing a membrane lining.

During the time that the reservoir was at the elevation of 2926 m (9600 ft), several of the observation wells in the hillside south of the reservoir showed an upward trend in the groundwater level. The upward trend was most noticeable in the wells located in the vicinity of the southeast corner of the reservoir. As of June 1979, four observation wells indicated increases of 1.5, 2.0, 0.8, and 0.2 m (4.8, 6.7, 2.5, and 0.8 ft), with increasing distance from the reservoir. Four other observation wells, adjacent to the reservoir rim, had shown increases of 0.09 to 0.11 m/mo (0.3 to 0.35 ft/mo) since installation in August 1978. Other observation wells around the south rim of the reservoir remained steady or decreased, with the exception of two which increased significantly.

By August 1979, it had become apparent that the reservoir was causing a rise in the groundwater levels in the hillside between the forebay reservoir and the powerplant. Subsurface drains would be ineffective due to the size of the reservoir and the nonuniformity of the various sand and gravel layers underlying the reservoir and hillside. Concern that the rising ground water

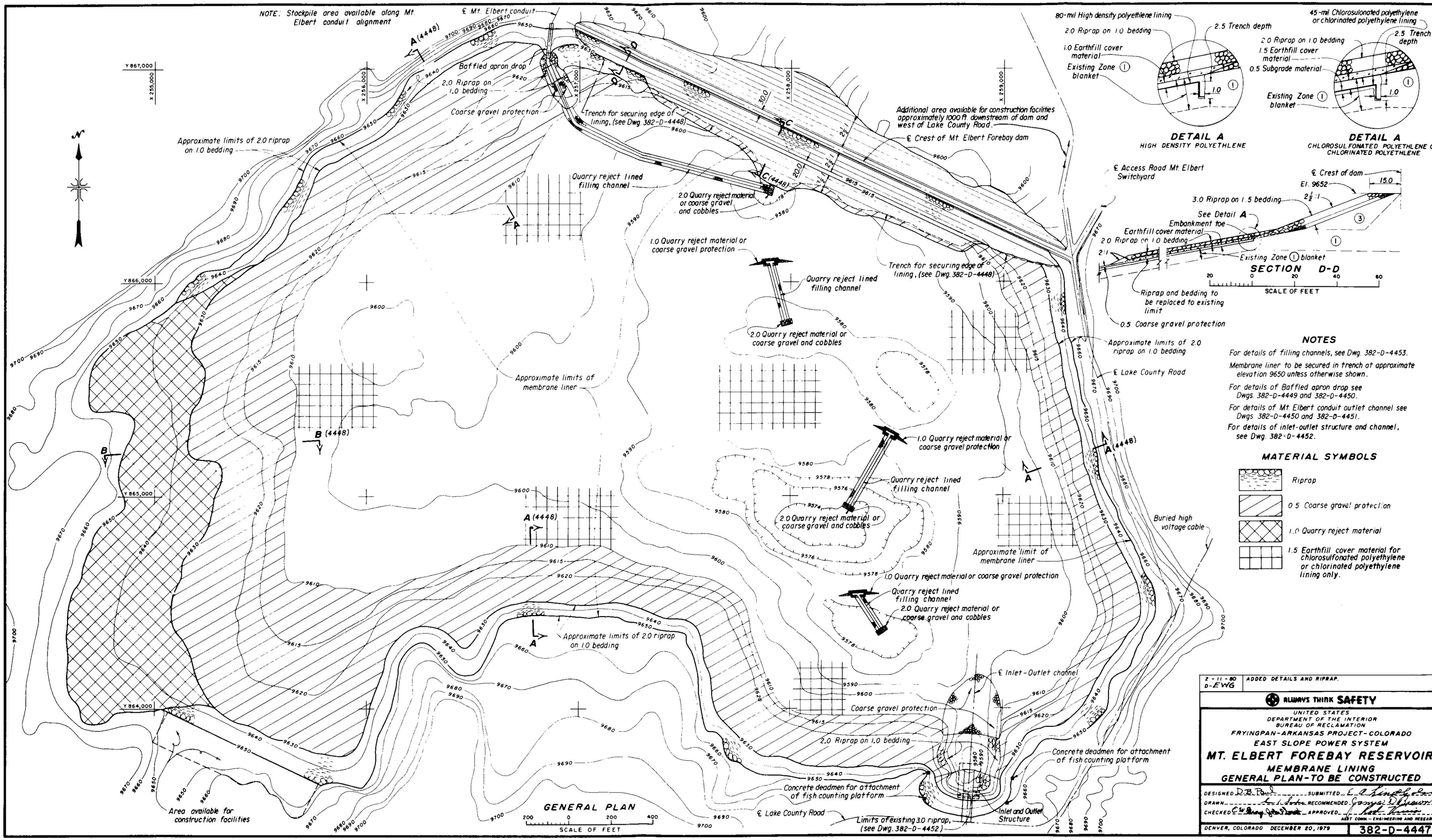


Figure 1.—Membrane lining—general plan.

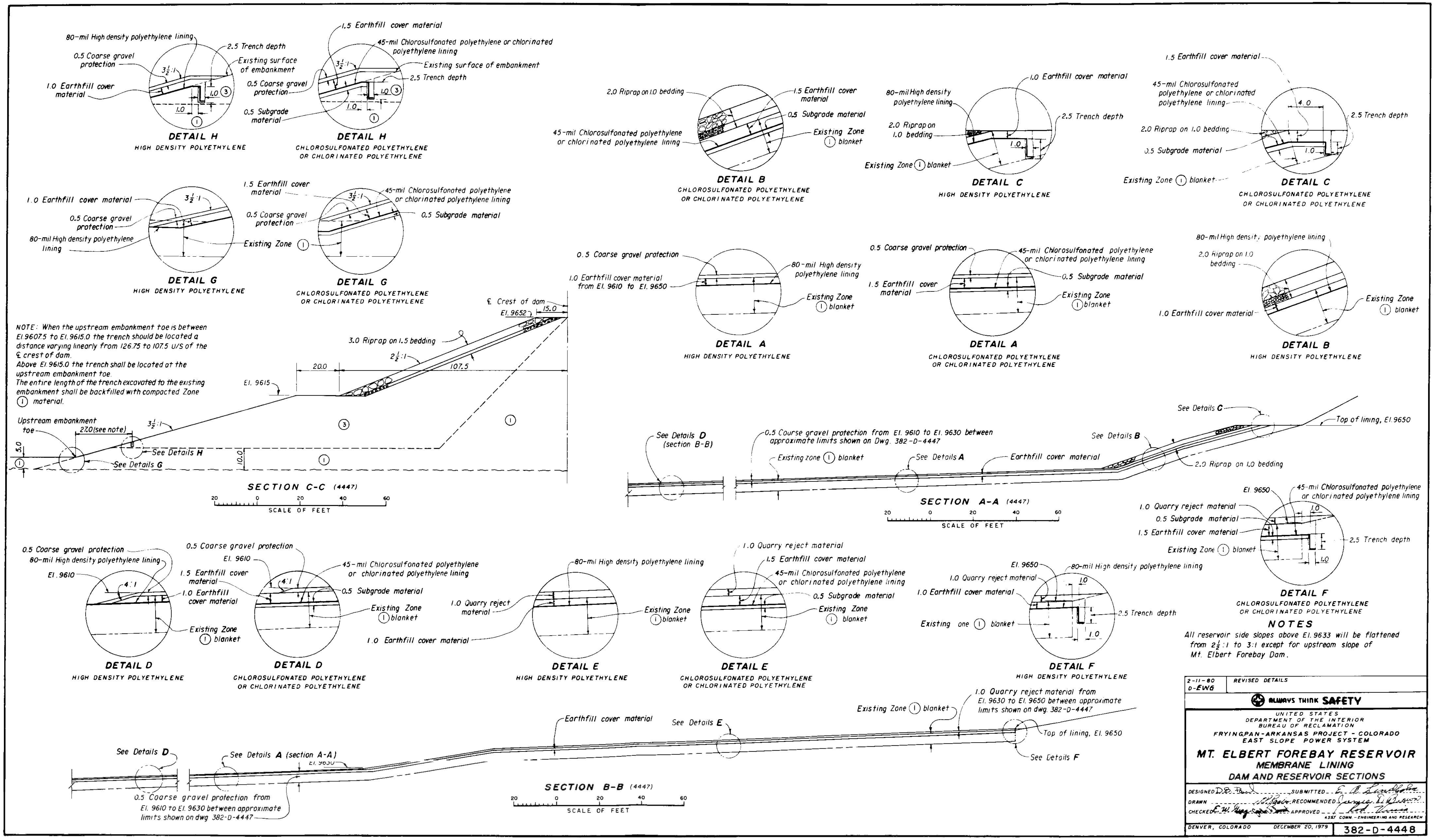


Figure 2.—Membrane lining—dam and reservoir sections.

Figure 3.—Aerial view looking south across the forebay reservoir. The first portion of placed membrane lining is visible in the near right side of the reservoir and the processing plant is located in the center of the reservoir area. Also, the inlet-outlet structure (upper left-hand corner), forebay dam (foreground), slope protection material around the perimeter of the reservoir, and subgrade areas being prepared by the contractor are visible. Photo C-382 706-14510 NA.

could lessen the stability of the hillside and reactivate the ancient landslide led to the decision in August 1979 to place an impervious membrane in the forebay reservoir.

In September 1979, Dr. Frank Patton, a consulting engineering geologist, was retained to study the hillside stability problem. He concluded that "the present reservoir seepage condition is significantly increasing the pore water pressures in the hillside and, therefore, should be considered a principal destabilizing factor." He recommended that the reservoir be drained immediately, and that an impervious membrane be required for lining the upper (forebay) reservoir. This confirmed the Bureau's decision to line the reservoir.

Selection of Membrane Lining

Installation of a membrane lining under the conditions at Mt. Elbert was unprecedented in USBR construction. An intensive effort was, therefore, made to investigate all critical requirements of a membrane lining for long-term service under the unique and severe climatic and operating conditions to be encountered at Mt. Elbert. The reservoir located in a high mountainous terrain, can be subjected to severe daily and seasonal temperature extremes, high winds, and thick ice formation in the winter. Also, the maximum head in the reservoir will be 21 m (70 ft) with the water level fluctuating approximately 9 m/week (30 ft/week) as a result of the pump-generating operations.

Alternative linings such as portland cement concrete and asphaltic concrete were investigated.

However, they were rejected for the following reasons:

1. They would require the production of large amounts of aggregate,

2. They probably require more than one construction season, and

3. Water loss through the asphaltic concrete due to cracking and primary permeability would be comparable to that through the existing earth lining.

During the selection process, the USBR contacted various manufacturers and fabricators of lining materials, inviting their advice and counsel on the Mt. Elbert installation. Also, other organizations that had installed reservoir linings were contacted. USBR personnel visited several large flexible membrane lining installations under construction in Colorado during the summer of 1979 [4].

The investigation, conducted in the 4 months available, revealed few similar installations and none with extended service records on currently produced membranes. The study indicated that membrane formulations changed frequently as industry corrected weaknesses in earlier products and sought to exploit new technology to improve materials. Effective factory and field seaming methods were recognized as critical. Also, a heavy earth cover was deemed essential to long service under severe climatic conditions. Literature data provided only fragmentary and inconclusive records regarding the long-term properties and performance of current products. Even though standard testing methods for various membrane properties existed, the overall QA Program had to be generated for both plant fabrication and field installation of the membrane. The large volume of materials also required obtaining assurances that suppliers could meet the demand on short notice.

The investigation affirmed that a membrane lining was best suited for the purpose of providing a tight, durable lining for the forebay reservoir. Based on the "state-of-the-art" survey, availability of materials, time frame to accomplish the work, and costs, specifications were prepared in the fall of 1979 and issued in January 1980. Alternate bidding schedules for installation of any one of three lining materials were included in the specifications. These included 1.14-mm (45-mil) CPER (reinforced chlorinated polyethylene), 1.14-mm RCSPE (reinforced chlorosulfonated polyethylene), and 2-mm (80-mil) HDPE (high-density polyethylene). The low bidder selected CPER.

CONCLUSIONS

1. *Lining Selection.* —

a. Variability of basic polymer formulations, in manufacturing techniques, in fabricating, in lining placement procedures, and field seaming all made final selection of lining materials and installation procedures very difficult for the Mt. Elbert installation. Although thousands of linings have been installed throughout the world, long-term, reliable performance records on a particular polymer formulation were nonexistent. Also, information on similar lining installations with this particular site and environmental conditions could not be obtained.

b. After a short, intensive investigation involving limited laboratory studies, discussions with manufacturers and users of flexible membrane linings, and visits to ongoing installations, three materials, representing the latest "state-of-the-art," were selected for inclusion in the specifications. The materials included 1.14-mm (45-mil) CPER (reinforced chlorinated polyethylene), 1.14-mm RCSPE (reinforced chlorosulfonated polyethylene), and 2-mm (80-mil) HDPE (high-density polyethylene). For this work the low bidder selected CPER.

2. *Earthwork and Lining.* —

a. Efficient handling and processing of earth materials by the prime contractor were the keys to completing the job on schedule. Sufficient manpower and equipment were used very effectively. The contractor was also very cooperative regarding several changes which had to be made when it became apparent that some types of earth materials would be in short supply.

b. To complete the job within the time constraints, it was necessary for the prime contractor to work in several areas within the reservoir at the same time. This in turn limited the areas where the lining subcontractor could work and, on occasion, resulted in newly installed lining being joined to lining which had been placed much earlier in the job. Consequently, considerable time and effort were expended to clean the previously installed lining for seaming.

c. The membrane lining fabrication and installation were very labor intensive. Industry needs to develop more efficient methods of making factory and field seams. Also, more efficient methods are needed for the handling and placement of the individual membrane blankets.

d. Better storage and unloading facilities should have been available at the jobsite to reduce mechanical damage to the as-received blankets.

e. The lining should be installed so that all seams, both factory and field, run perpendicular to the slope rather than parallel to the slope. Such placement would reduce the stress on the seams, especially during earth cover placement.

3. *Quality Assurance Program.* —

a. The QA (Quality Assurance) Program was very effective and contained the best state-of-the-art inspection and testing techniques. Probably the most valuable part of the QA Program was the field inspections, both factory and especially jobsite. Thorough jobsite inspections assured the Bureau of a top quality installation or the best available with present technology. The extensive physical property testing assured the Bureau that the material being used in the installation met all Mt. Elbert specifications.

b. A preconstruction conference should have been held between the USBR and lining manufacturing personnel involved in QA work to review and agree on the interpretation of the various ASTM testing methods and results. This procedure would have minimized discrepancies in the test results.

c. The specification requirement for third-party verification of the CPER membrane lining proved to be a useful QA measure.

d. The seam peel strength test for factory and field seams was an unspecified USBR QA test which provided important additional information as to seam quality. This test should be incorporated in future specifications.

e. Air lance testing proved to be a quick and effective method for checking the bonded overlap of both the factory and the field seams. It was especially effective in the repair and final acceptance of the adhesive field seams.

f. Field cutout samples proved to be a good check on the quality of the field seams. Field fabricated samples generally did not provide as good a check on quality.

INSTALLATION

General

The principal features of work covered by the specifications for the Mt. Elbert Forebay Reservoir membrane lining include: removal of all existing slope protection; excavating and processing the top 0.61 m (24 in) of the impervious earth lining; preparation of the subgrade; manufacturing, fabrication, testing, and installation of the membrane lining; placement of the earth cover; and replacement of the slope protection. A distribution chart for the earth materials is shown on figure 4.

Earthwork

Excavation. —Riprap placed on the reservoir side slopes during the original construction of the forebay reservoir was excavated prior to installation of the membrane lining and stockpiled in various locations around the reservoir bottom.

The 0.3 m (12 in) of existing bedding for riprap was excavated and used in the gravel slope protection areas. It was originally planned to excavate, stockpile, and reuse the bedding. Further consideration indicated that excavation of the bedding could not be done without including some of the underlying earth lining. Therefore, the decision was made to reuse the bedding materials to supplement other areas of protection for the earth cover.

The original side slopes extended from elevations of 2941 to 2935 m (9650 to 9630 ft) at an approximate slope of 2½:1 (horizontal to vertical). During discussions with lining manufacturers, it was indicated that the side slopes should be no steeper than 3:1. They pointed out instances where tracked vehicles trying to push large amounts of earth material up slopes steeper than 3:1 had begun to stall, spun their tracks through the earth cover, and damaged the liner. In addition, the stability of the earth cover would be improved. Based upon this information, the side slopes were flattened to 3:1.

Slopes in the immediate vicinity of the inlet-outlet structure which were steeper than 3:1 remained at their original inclination where necessary to conform to the outlines of the concrete structures. The 0.3 m (12 in) of quarry reject material previously placed on the 20:1 beaching slope in the western portion of the reservoir were excavated. All rocks larger than 75 mm (3 in) in size were separated out to obtain the additional riprap needed due to flattening the reservoir side slopes from 2½:1 to 3:1. The 0.15 m (6 in) of coarse gravel protection between the elevations of 2935 and 2931 m (9630 and 9615 ft) were excavated and stockpiled for reuse.

Five filling dikes and channels located in the east half of the reservoir had been constructed prior to initial filling of the reservoir to direct and control the flow into the natural depressions and thereby prevent erosion of the earth lining. The materials excavated from these dikes were reused as directed by the field engineer.

The 1.5-m (5 ft) thick earth lining was excavated (fig. 5) to a maximum depth of 0.61 m (24 in) for the purpose of providing earth material for the membrane liner subgrade and earth cover. On the 2½:1 reservoir side slopes above an elevation of 2938 m (9640 ft), up to 0.91 m (36 in) were excavated to facilitate flattening the slopes to 3:1. Excavation adjacent to concrete structures was, in some cases, greater than 0.61 m (24 in) in order to keep the riprap and coarse gravel slope protection to the same grade as before excavation. Final excavation lines were transitioned as necessary to provide a smooth surface free of abrupt changes.

Processing Plant (figs. 6 and 7).—It was important that the membrane lining be placed upon a subgrade that did not contain gravel or cobbles which could puncture it. Before placement, subgrade material, obtained from the excavation of the existing earth lining, was processed to remove all particles larger than 25 mm (1 in). Crushing in lieu of separation was not permitted since that would result in angular fragments which could puncture the membrane lining. The contractor used a "harp screen" to remove the plus 25-mm (1-in) material. The "harp screen" (fig. 8) consisted of parallel wires on 25-mm (1-in) centers which could be tightened or loosened to change the screening characteristics, depending upon the type and properties of material. The earthfill cover material was also processed in this manner. The plus 25-mm (1-in) material was incorporated into the gravel slope protection areas. About 11 500 m^3 (15 000 yd^3) of minus 4.75-mm (No. 4) sieve material adhered to the plus 25-mm (1-in) material, and resulted in a shortage of processed material. The shortage was made up by placing 0.3 m (12 in) of earth cover followed by 0.15 m (6 in) of plus 25-mm (1-in) material and its adhering minus 4.75-mm (No. 4) material in selected areas. Approximately 765 000 m^3 (1 000 582 yd^3) of earth was processed during the project.

Subgrade Preparation.—Processed earth material was placed and compacted to a minimum depth of 0.15 m (6 in) as a subgrade for the membrane lining (figs. 9-14). To compact the subgrade material and to obtain a smooth surface, two passes of a pneumatic-tired roller followed by two passes of a vibratory steel roller provided satisfactory results. As a final step in obtaining as smooth as possible subgrade, hand labor was used to remove loose or protruding gravel and other materials which could puncture the membrane.

Cover Material.—A minimum of 0.45 m (18 in) of processed earth was placed over the membrane lining except where plus 25 mm (1 in) replaced the upper 0.15 m (6 in). To protect the lining from mechanical damage during construction, vehicles were not allowed to operate directly on it. Consequently, the earth cover was initially dumped at the edge of the lining (fig. 15) and, thereafter, spread over the membrane by dozers (figs. 16 and 17), maintaining the 0.45-m (18-in) depth between the lining and equipment. Compaction of approximately 95 percent of laboratory Proctor maximum density was achieved by equipment traffic. In addition to aesthetic and environmental considerations associated with the aquatic life, the earth cover was placed over the membrane liner for protection against:

1. UV (ultra-violet) degradation

2. Animal traffic

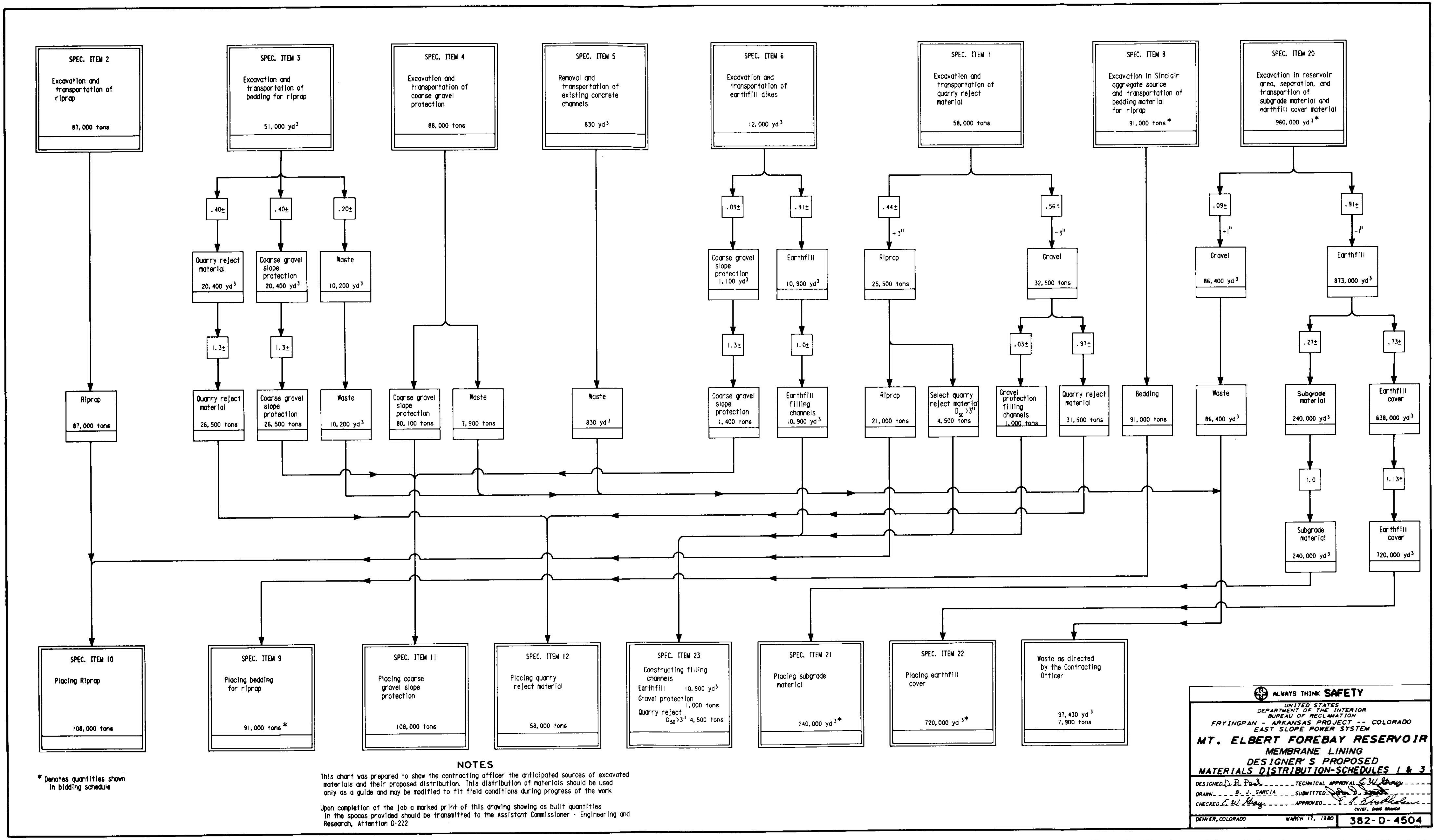


Figure 4.—Membrane lining—designer's proposed materials distribution.

Figure 5.—Excavating the existing gravel slope protection from the 1.5-m (5-ft) earth lining. Photo P-801-D-79726

Figure 6.—Processing plant used to separate plus 75-mm (3-in) size rock from the quarry reject material. This material was used to supplement the existing rock riprap. Photo P-382-706-28090 NA

Figure 7.—Processing plant used to separate the minus 25-mm (1-in) material from the 0.61 m (2 ft) of excavated earth lining. Photo P-801-D-79727

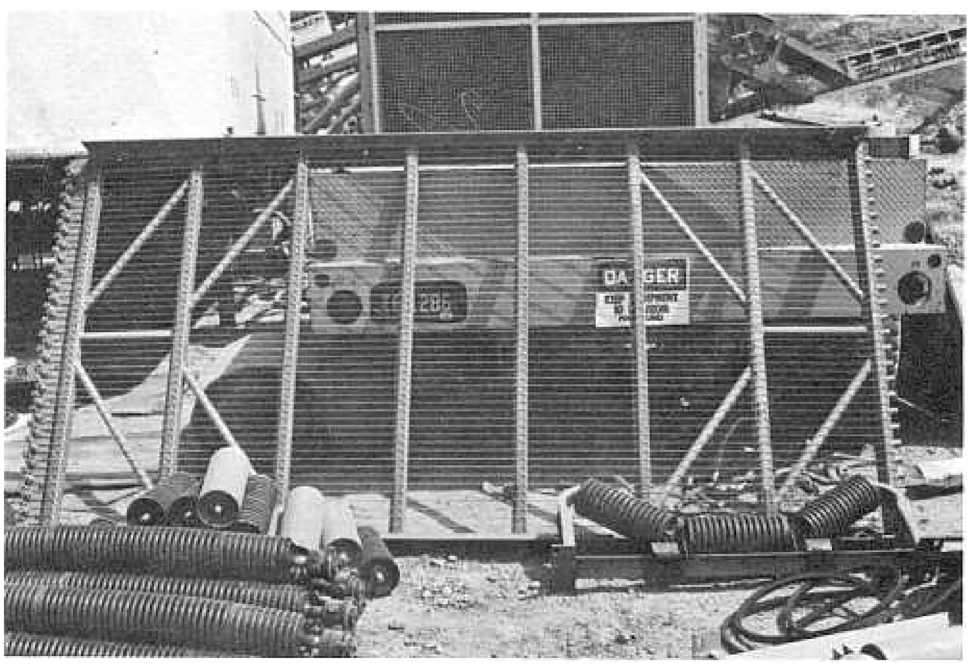


Figure 8.—Closeup view of harp screen used to separate plus 25-mm (1-in) material from the 0.61 m (2 ft) of excavated earth lining. The tension in the wires which comprise the screen can be increased or decreased to alter the screening properties. Photo P-382-706-28254 NA

Figure 9.—Spreading minus 25-mm (1-in) subgrade material. Photo P-801-D-79728

Figure 10.—Placing subgrade material on 3:1 reservoir side slopes. Photo P-801-D-79729

Figure 11.—Pneumatic-tired roller used initially to compact the subgrade material. Photo P-801-D-79730

Figure 12.—Vibratory smooth-drum roller used for final rolling of subgrade. Photo P-382-706-28235 NA.

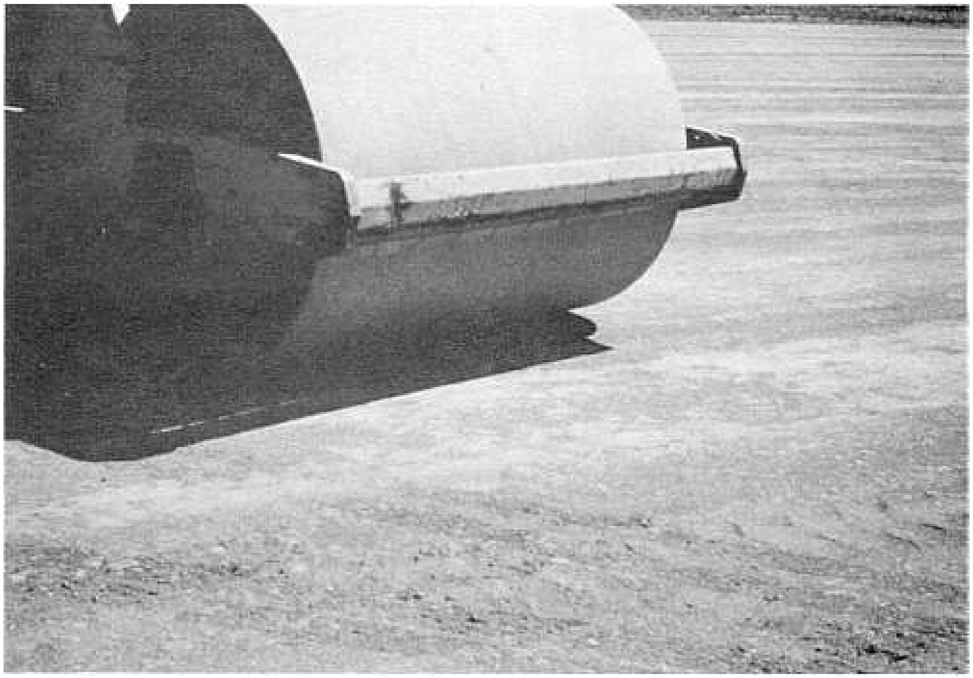


Figure 13.—Closeup view of subgrade upon completion of rolling. Subgrade at bottom of photo has not been rolled. Photo P-801-D-79731

Figure 14.—Laborers walking across subgrade, prior to placement of the membrane liner, removed all rocks which could puncture the liner. Photo P-382-706-28229 NA

Figure 15.—Initial placement of 0.45-m (18-in) earth cover consisting of minus 25-mm (1-in) material. Photo P-801-D-79732

Figure 16.—Dozer spreading 0.45-m (18-in) earth cover material. Large clods of earth were the result of dessication of minus 25-mm (1-in) material while on the stockpile. Photo P-801-D-79733

Figure 17.—Placement of 0.45-m (18-in) earth cover on 3:1 reservoir side slopes. Material was dumped at the toe of slope by scrapers and then pushed up the slope by dozers. Note presence of inspector. Photo P-801-D-79734

3. Ice action

4. Vandalism

5. Wind

6. Mechanical damage during construction and operation

Slope Protection Material.—Once the earth cover was placed over the liner, the slope protection material was replaced. New bedding material was hauled 3.2 km (2 mi) to the forebay by bottom-dump trucks from an aggregate source located west of the Mt. Elbert Powerplant. The riprap was replaced from the top to the bottom of the slope (fig. 18) by crawler tractors with rock buckets. The plus 75-mm (3-in) quarry reject material used to provide additional riprap was mixed with the existing riprap rather than being used solely in one area.

The minus 75-mm (3-in) portion of the quarry reject material together with sand, gravel, and cobbles from the old bedding was placed on the 20:1 beaching slopes between elevations 2941 and 2935 m (9650 and 9630 ft) (fig. 1). The coarse gravel protection stockpiled around the reservoir, together with the plus 25-mm (1-in) material, was used to blanket the earth cover between the elevations of 2935 and 2926 m (9630 and 9600 ft).

Four filling channels were reconstructed in the east half of the reservoir to direct filling flows to low areas without eroding the earth cover.

Membrane Installation

The CPER lining material (fig. 19) is of three-layer construction consisting of two equal thicknesses of CPE (chlorinated polyethylene) laminated to one layer of 10 by 10, 1000-denier polyester scrim. The physical properties requirements for this lining are given in table 1.

The lining was factory fabricated into "blankets," each 1300 m² (14 000 ft²) in size and weighing approximately 2268 kg (5000 lb). Two shapes of blankets were furnished: 61 by 21 m (200 by 70 ft), containing 14 factory seams made with a Leister™ hot-air gun; and 30 by 43 m (100 by 140 ft), containing 29 factory seams made dielectrically. The latter shape was designated

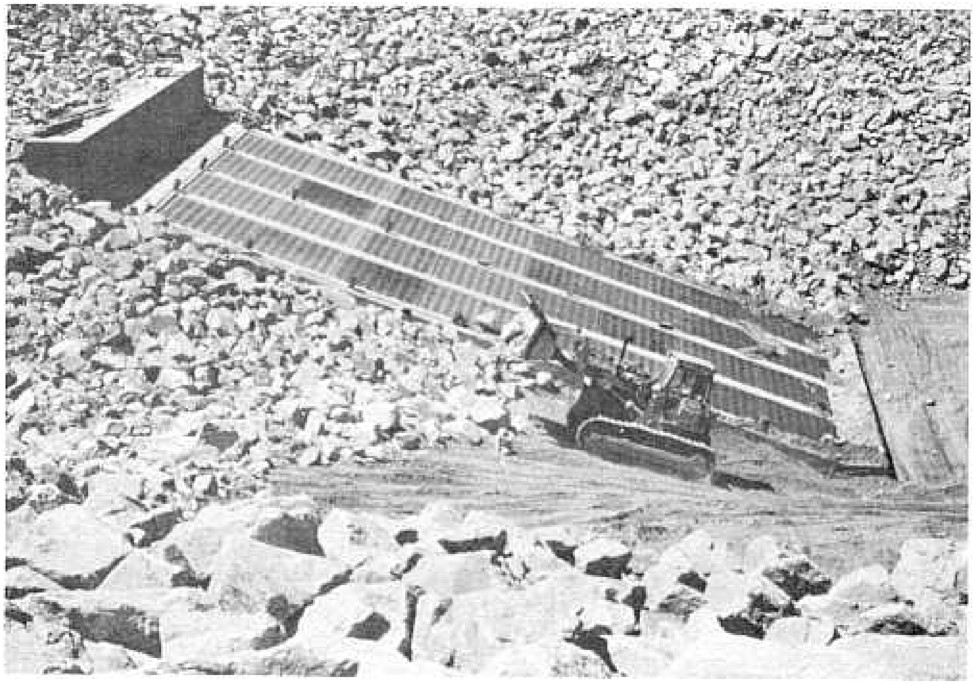


Figure 18.—Placement of riprap adjacent to inlet-outlet structures. Photo P-801-D-79735

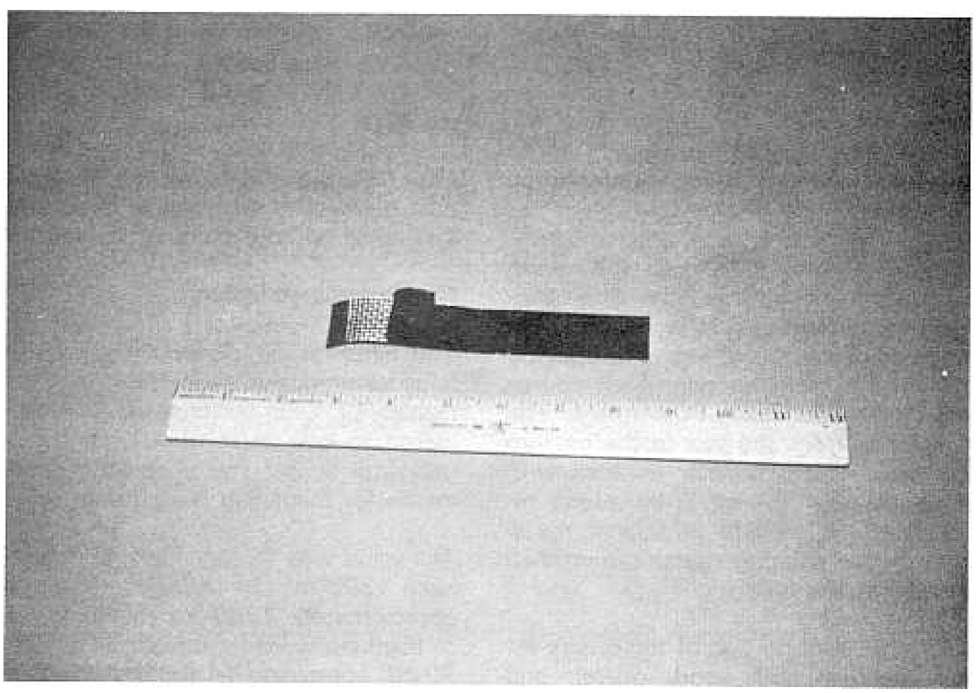


Figure 19.—Sample of CPER lining consisting of two outer plys of 0.51-mm (20 mil) CPE and an inner ply of 10 × 10, 1000-denier polyester reinforcing scrim. Photo P-801-D-79736

Table 1.—*Test methods used on the 1.14-mm (45-mil) CPER blanket samples*

Property	Test method	Minimum requirement	No. of specimens tested per blanket sample
Thickness	ASTM: D 751-79	1.04 mm (0.041 in)	(random readings)
Breaking strength, each direction	ASTM: D 751-79 Grab Method - A	890 N (200 lbf)	5 (warp direction) 5 (fill direction)
Tear strength, each direction	ASTM: D 751-79 Tongue Tear Method - B	334 N (75 lbf)	5 (warp direction) 5 (fill direction)
Bonded seam[1] strength in shear	ASTM: D 751-79 Grab Method - A	Equals parent material breaking strength	5
Bonded seam [1] strength in peel	ASTM: D 1876-78	No specs. requirement	5
Dimensional stability (percent change, maximum)	ASTM: D 1204-78 1 hour at 100 °C (212 °F)	2 percent	2
Low temperature bend	ASTM: D 2136-78 3-mm (⅛-in) mandrel; 4 hours at −40 °C (−40 °F)	Pass	5
Hydrostatic resistance	ASTM: D 751-79 Method A	2.07 MPa (300 lb/in^2)	5
Ply adhesion	ASTM: D 413-76 Machine Method Type A Specimens	1400 N/m (8 lb/in)	5
Infrared spectroscopy	B.F. Goodrich lab. procedure	Matching IR scan	2
Total specimens per blanket			49

[1]These same test methods were used on all seam samples taken in the field.

primarily for installation on the side slopes. For delivery to the jobsite (fig. 20), the blankets were accordion-folded, rolled, palletized, and transported via commercial truck. About 930 blankets were installed in the forebay reservoir in approximately 84 workdays.

Initially, the installer used one labor crew of approximately 18 to 20 people to install the blankets. After details of the installation procedure were developed, an additional crew was obtained.

To install the membrane lining, the labor crews unfolded and positioned the blankets (figs. 21 to 24). Adjacent blankets were overlapped a minimum of 0.15 m (6 in). A three-man crew thoroughly cleaned the contact surfaces with trichloroethylene solvent, and the manufacturer's bodied-solvent CPE adhesive was applied to a minimum width of 100 mm (4 in) (figs. 25 to 28). The field seams were then hand rolled (fig. 29) and allowed to cure a minimum of 4 hours before air testing to detect any weak or unbonded areas. The air test (figs. 30 and 31) consisted of air at 345 kPa (50 lb/in^2), supplied through a 5-mm (3/16-in) nozzle directed at the seam. After the field seams were tested and approved, a cap strip was applied over the field seam. The cap strip was a 0.76-mm (30-mil) thick unsupported CPE, 75 mm (3 in) wide.

For installation on the reservoir side slopes, an anchor trench 0.3 m (1 ft) wide and 0.76 m

Figure 20.—The 2268-kg (5000-lb) palletized membrane lining as received at jobsite. Photo P-801-D-79737

Figure 21.—Modified front-end loader used to transport and unroll membrane lining around jobsite. Photo P-382-706-28238 NA

Figure 22.—Modified front-end loader unrolling membrane lining on prepared subgrade. Photo P-801-D-79738

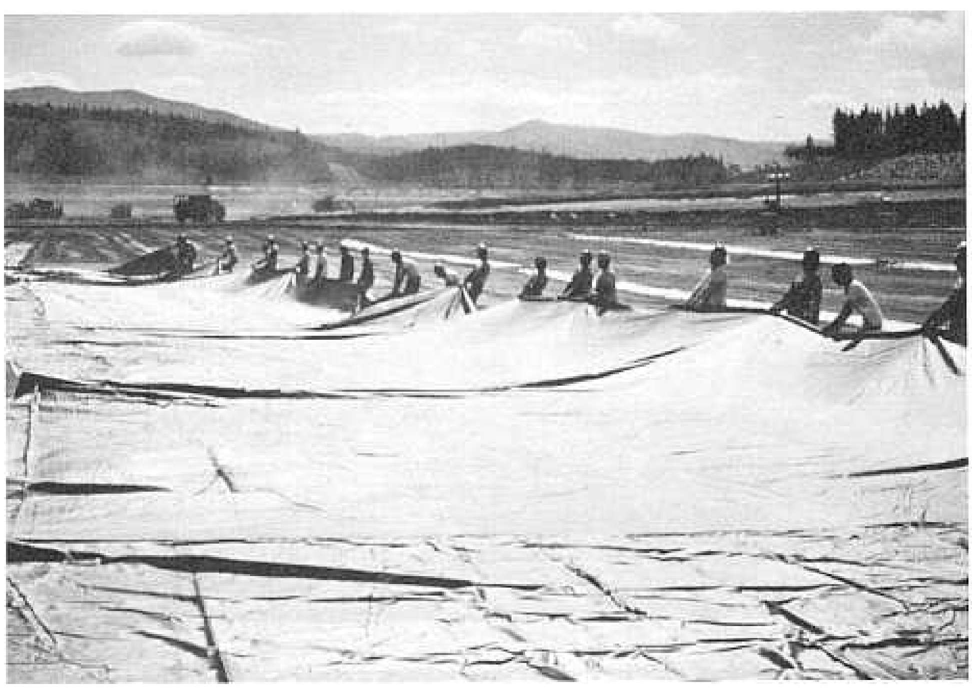


Figure 23.—Labor crew unfolding and positioning membrane lining blankets. Photo P-801-D-79739

Figure 24.—Installation of the reservoir membrane lining on the side slopes. Note tires used to hold down lining against wind. Photo P-801-D-79740

Figure 25.—Three-man crew performing consecutive seaming operations. Note 0.45-m (18-in) earth cover placement on side slope in the back ground. Photo P-801-D-79741

Figure 26.—Cleaning of CPER lining with solvent. Photo P-801-D-79742

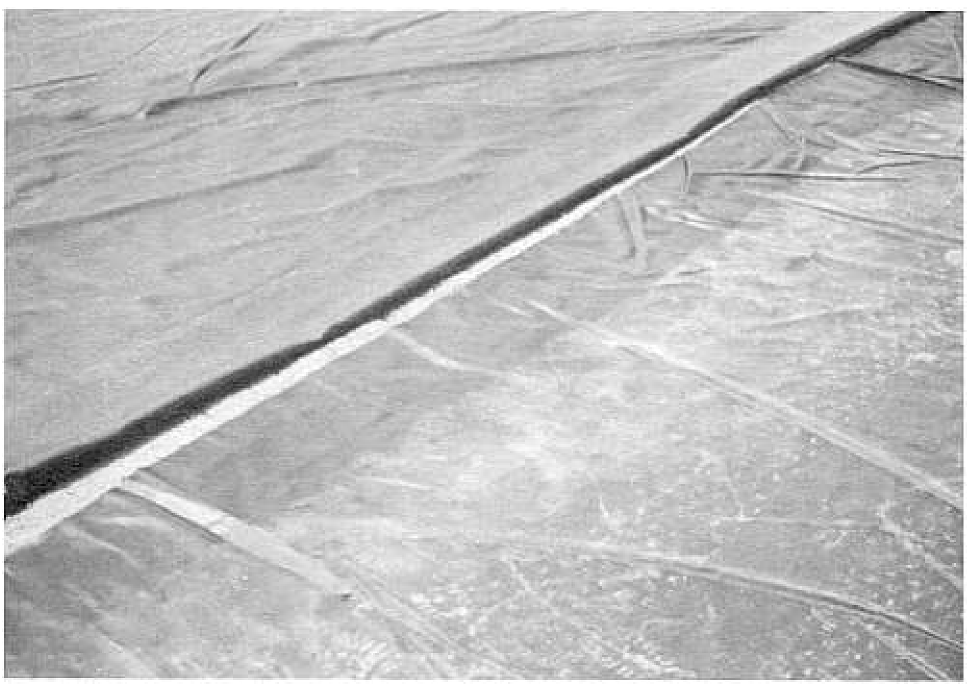


Figure 27.—Overlap seam area cleaned and ready for seaming. Photo P-801-D-79743

Figure 28.—Application of bodied solvent adhesive on prepared overlap seam area. Photo P-801-D-79744

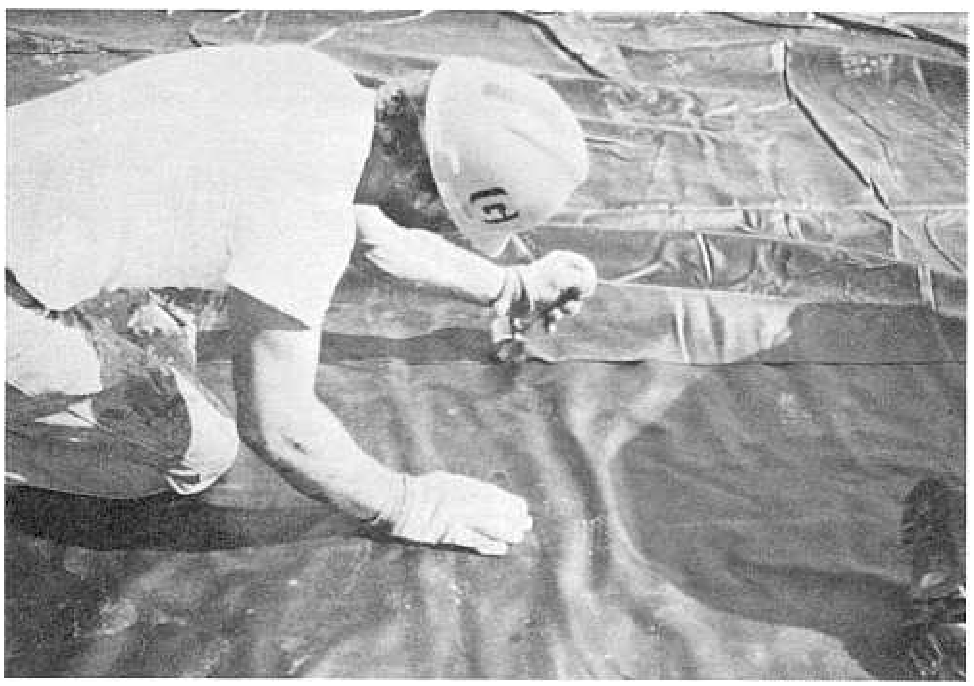


Figure 29.—Hand-rolling seam after application of bodied-solvent adhesive. Rolling is progressing from left to right of photograph. Photo P-801-D-79745

Figure 30.—Air-testing field seams. Photo P-801-D-79746

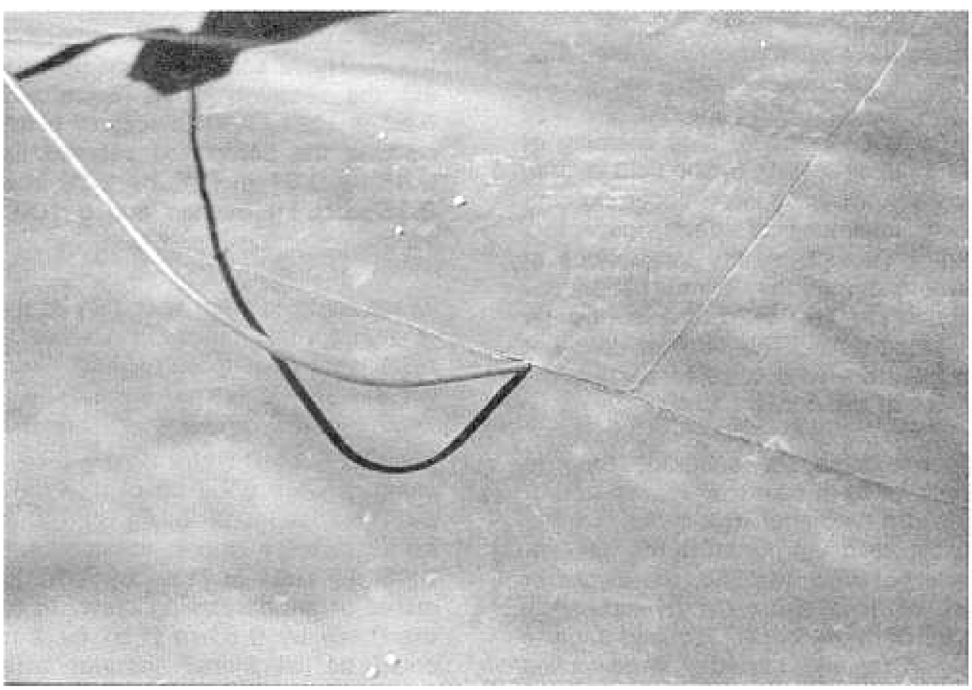


Figure 31.—Air test showing defective, unbonded section of overlap seam. Photo P-801-D-79747

(2.5 ft) deep was excavated with a tractor-mounted backhoe at the top of the slope around the perimeter of the reservoir (fig. 32). After the lining was placed down and across the bottom of the trench, the trench was backfilled and compacted (figs. 33 and 34).

The membrane lining was also terminated in an anchor trench in the impervious material at the toe of the embankment. The forebay dam contains an impervious core tied into the reservoir earth lining. The trench was backfilled with compacted, impervious material.

For installation around the inlet-outlet structures, the manufacturer's recommended procedure for attaching the membrane liner to concrete was followed (figs. 35 to 37). The concrete surface was cleaned of all foreign material and coated with the manufacturer's contact adhesive. The lining was cleaned with solvent and also coated with contact adhesive. All adhesive was allowed to dry until it became tacky. The lining was then pressed against the concrete and rolled with a steel roller. Redwood batten strips were bolted to the concrete and used to anchor the lining to the structures. The joint between the batten strips and concrete structure was calked to form a watertight seal.

Field Inspection

USBR inspectors were present at all times when the contractor's personnel were laying the blankets on the prepared subgrade. At any time during the installation process, field seaming of the blankets, air lance testing of the field seams, and cap stripping may have been occurring simultaneously. A minimum of three inspectors were required to provide quality inspections of all these different operations. In most instances 4 to 5 inspectors per 18- to 20-man labor crew were present at all times. This number does not include the inspectors who were inspecting the earthwork phase of the construction.

They visually inspected the subgrade prior to laying the blankets to ensure that it was free of depressions, wet areas, and large rocks or other sharp objects which could puncture the blanket. Prior to initiation of field seaming, the inspector ensured that the blankets were overlapped a minimun of 0.15 m (6 in) as required by the specifications. After the blankets were pulled into position, each panel and factory seam was examined for any defects or punctures that required patching (fig. 38). The seaming of the blankets was monitored closely to ensure that the minimum 100-mm (4-in) wide seam was produced. After the field seams were completed and allowed to cure, they were air tested. Any defective or unbonded areas were marked and repaired prior to application of the cap strip. The air lance test was invaluable and should be specified for all jobs involving similar lining materials.

Upon completion of the field seaming, the full length of all factory and field seams were again inspected to ensure that all defective areas were repaired or completed. Once accepted, the blankets were covered with the processed earth. Approximately 80 km (50 mi) of field seams were produced in joining some 930 blankets together.

To check the seaming method and integrity of the resultant seams, the following samples were taken daily:

1. One 0.61- by 0.61-m (2- by 2-ft) random sample of a field seam was cut from the lining each day (fig. 39).

2. A field fabricated sample seam was made for every 305 m (1000 ft) of field seam made. These samples were prepared by having the seaming crews seam two 0.3- by 0.61-m (1- by 2-ft) pieces of similar material so that the completed seamed sample was 0.45 by 0.61 m (1½ by 2 ft) in size with a 0.15-m (6-in) overlap and a 100-mm (4-in) seam.

These samples were sent daily to the E&R (Engineering and Research) Center where QA tests were conducted to determine the integrity of the field seams.

The 0.61- by 0.61-m (2- by 2-ft) field seam samples were good checks of the quality of the field seaming being performed. These samples were more meaningful than the 0.45- by 0.61-m (1½- by 2-ft) samples required of each seaming crew. In future jobs, the 0.45- by 0.61-m (1½- by 2-ft) samples could be eliminated without affecting the quality of the field seams.

Figure 32.—Excavation of anchor trench by backhoe at top of reservoir side slope. Uncompacted area on the reservoir side of the trench was the source of the plus 25-mm (1-in) material which got under the membrane and had to be removed by cutting and patching the membrane. Photo P-382-706-28158 NA

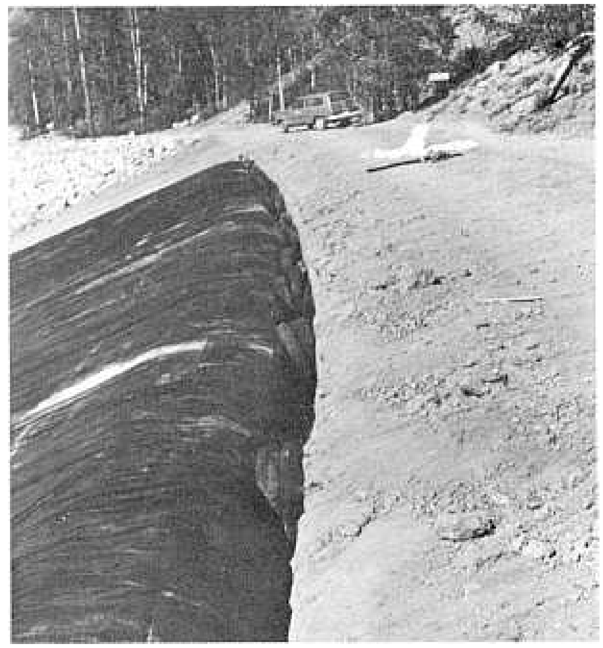


Figure 33.—Membrane lining temporarily anchored with rubber tires prior to backfilling. Photo P-382-706-28163 NA

Figure 34.—Compaction of the backfill material in the anchor trench. This portion of the anchor trench was in the perimeter of the access road (top of photograph). This type of compaction may result in less stress on the liner than compaction by the wheels of the construction equipment. Photo P-801-D-79748

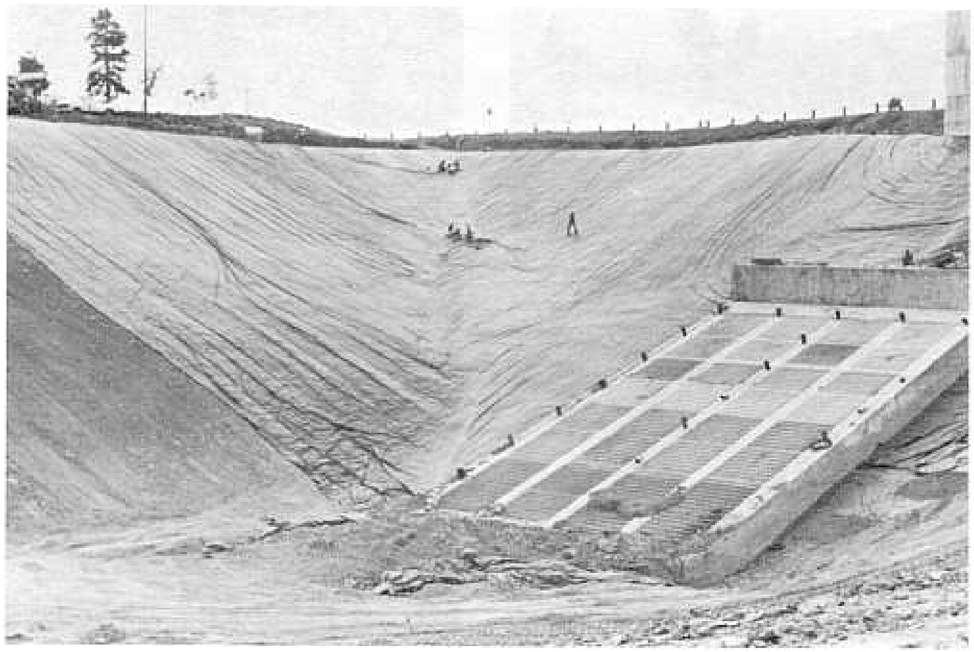


Figure 35.—Membrane lining installation around the inlet-outlet structure. Photo P-382-706-28466 NA

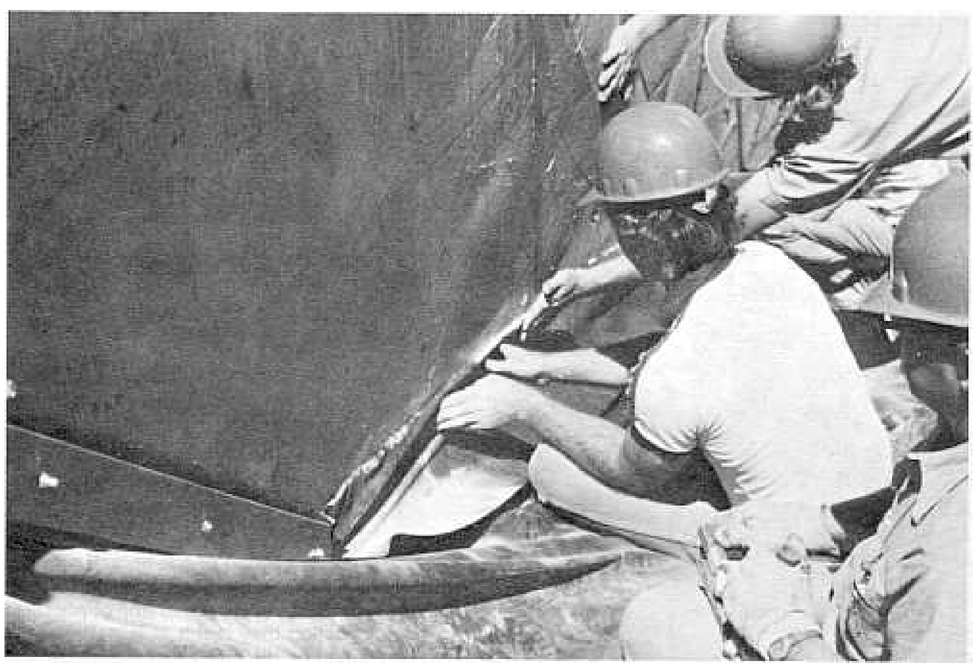


Figure 36.—Attachment of membrane lining to inlet-outlet structure using contact adhesive. Photo P-382-706-28460 NA

Figure 37.—Attaching redwood batten boards to finalize anchoring of membrane lining to inlet-outlet structure. Photo P-801-D-79749

Figure 38.—USBR inspector marking defective area on membrane lining for repair. Photo P-801-D-79759

Figure 39.—USBR inspector cutting out daily field seam samples. Photo P-801-D-79750

Special Field Studies and Observations

In addition to the QA Program discussed in the next section, special studies were conducted and observations were made in the field to gain additional information on the CPER performance and construction methodology. A synopsis of each of the observations and special studies follows:

Field test of thermal infrared scanner.—In an effort to field check the bodied-solvent adhesive, a thermal IR (infrared) scanning device was brought to the Mt. Elbert jobsite for testing the seam integrity. Briefly, the theory of the tests was the IR scanner detecting air voids or air pockets caused by imperfect bonding of the field seams. The scanner senses temperature differentials in its field of view and displays these differences on a CRT (cathode-ray tube), where warmer areas are white and cooler areas are black. Instrument sensitivity is nominally less than −16.7 °C (2 °F). The air pockets are cooler than the surrounding surface and show darker on the screen.

A total of five tests was conducted, two during daylight hours and three during the night. Areas to be tested were selected with the assistance of contractor and subcontractor personnel.

One night test was conducted for instrument calibration and to establish test procedures. The two daylight tests (9:30 a.m. and 2:30 p.m.) did not show thermal differences due to direct solar heating of the test areas.

The two night tests (9:30 p.m. and 4:00 a.m.) indicated gross areas of thermal differences caused by the uneven subsurface beneath the membrane. There was some indication of small air pockets, but the differences in coloration were not strong enough for positive identification.

Based on these tests, it appears that the following three factors prevented the identification of the air voids:

a. Moisture condensation under the membrane caused by thermal cooling after sunset. This moisture acted as a heat sink and barrier causing a uniform distribution of the thermal energy.

b. Presence of numerous air pockets caused by the uneven surface underneath the membrane made it difficult to distinguish between areas of imperfect bonding and those caused by other factors.

c. The small size of the target air pockets tended to approach the resolution capability of the instrument.

After completing the five tests, it was determined to be impossible to differentiate imperfections in the field bonding process with the IR scanner.

Lining damage occurring during installation over moist or saturated subgrade conditions.—Several times during lining installation, placement and seaming were terminated due to rain. The specifications required that all areas of the subgrade that became saturated due to runoff must be thoroughly dried or the area must be excavated and dry, processed material be placed and compacted before the lining was installed. Some of the moist subgrade areas were inadvertently overlooked when the lining was placed. After or during cover material placement, there was evidence of subgrade failure after several passes of a 651 Caterpillar scraper/loader. When the rutted area was hand excavated, it was discovered that the CPER had failed in tension, subsequently in tear, causing subsidence of the cover material under load. These areas had to be excavated and patched. This observation confirmed the fact that a firmly compacted and relatively dry subgrade was a necessity for lining installation.

Localized point stressing of 1.14-mm (45-mil) CPER over loose aggregate.—Localized point stressing can occur under field construction conditions and hydrostatic loading, causing localized weakening of supported lining material. The specifications called for a smooth, firm subgrade surface free from surface irregularities which could not safely be bridged by the 1.14-mm (45-mil) CPER material. This requirement was in question during construction, and a field test was requested in an effort to study the effects of loose, large aggregate under the CPER lining.

On July 9, 1980, rounded and angular aggregate which varied in size from 12.5 to 38 mm (½ to 1½ in) was placed on a 3- by 6-m (10- by 20-ft) section of prepared subgrade, so as to simulate loose aggregate under the CPER blanket. A test section of CPER was then placed over the aggregate and 0.56 m (22 in) of loose, processed cover material was spread over the blanket section. The cover material was then compacted to a 0.46-m (18-in) depth with six passes of a fully loaded 651 Caterpillar scraper/loader, which resulted in a wheel loading of approximately 310 kPa (45 lb/in^2) and an average density of 1362 kg/m^3 (85 lb/ft^3) (slightly lower than the average density obtained during actual cover placement). The cover material was then removed and the lining test section was inspected for physical damage (fig. 40). Preliminary visual inspection of the liner indicated that neither puncturing nor tearing had occurred; however, the lining was obviously stressed over the aggregate (fig. 41). Figure 42 indicates the varying size and spacing between the aggregate.

The test section was brought back to the E&R Center for testing and evaluation. In an effort to determine the possible damage to the scrim within the sheet, the Mullen hydrostatic resistance test (ASTM: D 751, method A) was performed on 24 aggregate distressed areas. To compare results, undamaged samples were taken adjacent to the distressed areas and tested for hydrostatic resistance.

Table 2 gives the results of the Mullen hydrostatic testing of stressed versus unstressed areas of the CPER lining. As indicated, the aggregate-distressed areas generally showed a reduction in hydrostatic resistance. Of particular note are the statistical mean, standard deviation, and range which indicate an obvious deterioration in hydrostatic resistance with the mean of the distressed specimens being 689 kPa (100 lb/in^2) less than the unstressed specimens.

Six of the stressed specimens failed (fig. 43), where one side of the CPE laminate ballooned because of delamination occurring at the stressed area. Varying degrees of delamination was evident in all of the aggregate-distressed specimens and showed a weakening of the scrim/CPE laminated bond. This reaction to overburden pressure was suspected because of the low elongation property of supported membranes and results of hydrostatic pressure cell testing of 1.14-mm (45-mil) CPER over a 15- to 19.0-mm (3/8- to 3/4-in) subgrade which is discussed

Figure 40.—Inspection of lining test section to determine effect of loose aggregate on membrane lining. Photo P-801-D-79751

Figure 41.—Membrane lining exhibiting stressing after being placed over aggregate in figure 42. Photo P-801-D-79752

Figure 42.—Typical size and spacing of aggregate placed under the membrane lining test section. Photo P-801-D-79753

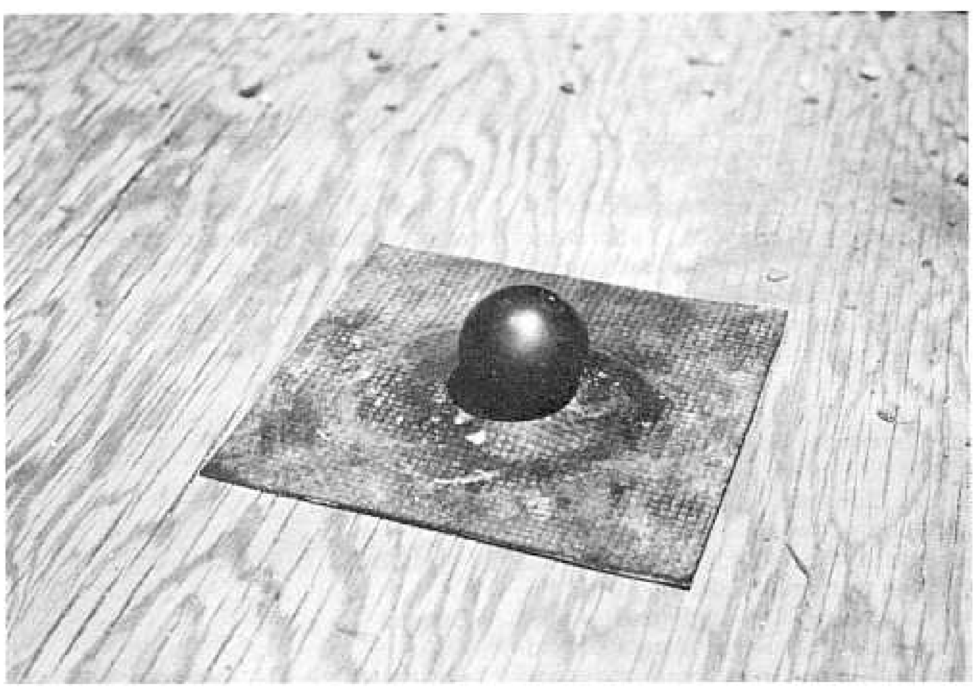


Figure 43.—Test specimen after Mullen hydrostatic testing. Delamination of lining has occurred due to aggregate point stressing. Photo P-801-D-79754

Table 2.—*Mullen hydrostatic test results of distressed versus unstressed 1.14-mm (45-mil) CPER*

Specimen Number	Approximate rock size mm (in)	Burst pressure over distressed area MPa (lb/in²)	Burst pressure over unstressed area MPa (lb/in²)
1	< 12 (< ½)	2.96 (430)	2.96 (430)
2	12-20 (½-¾)	2.14 (310)	3.03 (440)
3	< 12 (< ½)	3.00 (435)	3.14 (455)
4	< 12 (< ½)	3.03 (440)	3.17 (460)
5	20 (¾)	2.62 (380)	3.07 (445)
6	40 (1½)	1.62 (235)	3.10 (450)
7	40 (1½)	1.65 (240)	3.17 (460)
8	20 (¾)	1.69 (245)	3.10 (450)
9	< 12 (< ½)	2.90 (420)	3.21 (465)
10	20-40 (¾-1½)	1.39 (200)	3.03 (440)
11	20 (¾)	3.21 (465)	3.10 (450)
12	40 (1½)	2.93 (425)	3.10 (435)
13	25 (1)	1.31 (190)	3.17 (460)
14	12 (½)	2.90 (420)	3.31 (480)
15	20 (¾)	2.96 (430)	3.14 (455)
16	25 (1)	0.59 (85)	3.31 (480)
17	20 (¾)	3.10 (450)	3.03 (440)
18	25 (1)	2.96 (430)	3.03 (440)
19	12 (½)	2.90 (420)	2.96 (430)
20	25 (1)	3.14 (455)	3.29 (475)
21	25 (1)	2.96 (430)	3.17 (460)
22	12 (½)	3.21 (465)	3.07 (445)
23	20 (¾)	0.96 (139)	3.10 (450)
24	12 (½)	2.93 (425)	2.96 (430)
Mean		2.45 (356)	3.11 (451)
Standard deviation		0.81 (117)	0.10 (15)
Range		0.59-3.21 (85-465)	2.96-3.31 (430-480)

in more detail under Quality Assurance Program, subsection on Special Laboratory Studies. The hydrostatic pressure cell testing stressed the lining material over a moderately rough aggregate subgrade in an effort to study the creep properties of the supported membrane.

Although the membrane did not fail after 30 days at 414 kPa (60 lb/in²) (43 m (140 ft) of head), there was noticeable distress over the larger aggregate and within the voids. In particular, it was noted that the scrim fibers tended to separate within the membrane, allowing the CPE to creep and form over the aggregate. Additionally, the individual fibers were elongated and weakened. These findings reinforced the concern for proper smooth subgrade preparation and elimination of all loose surface aggregate over 12.5 mm (½ in) in size.

In addition to the above test, the cover material was excavated down to the lining at a haul road location where fully loaded 651 Caterpillar scraper/loaders had made over 200 passes. The lining did not experience any obvious damage; however, upon close observation it was noted that some point stressing had occurred over loose aggregate 12.5 mm (½ in) in size under the lining.

QUALITY ASSURANCE PROGRAM

General

An extensive QA program was conducted in conjunction with the Mt. Elbert flexible membrane lining installation. The procedures implemented for this program included:

1. Requiring the contractor to furnish toxicity data that showed the CPER membrane lining had no adverse effect on cold-water species of aquatic life present in the forebay reservoir.

2. Third-party verification of the chemical formulation of the CPER membrane lining to ensure that it met the specifications requirements.

3. An initial visit to the factory by the USBR personnel to inspect factory manufacturing and QA procedures, and to set up a cooperative QA program.

4. Requiring the contractor to submit for approval certified laboratory test reports on the physical properties listed in table 1 for each day's production of the CPER roll goods before fabricating them into blankets.

5. Weekly visits to the fabrication plants by USBR resident inspectors to view and monitor the factory seaming methods. During these visits, they also audited the shear test results for factory seams, and certified the results of low temperature tests.

6. Obtaining samples from every tenth blanket for testing and approval at the E&R Center in Denver.

7. Air lance testing all factory and field seams (involving approximately 789 km (490 mi) of seams).

8. Daily sampling, testing, and visual inspection of field seams and blankets as previously described under the section on installation.

Figure 44 is a schematic of the QA Program for approving the membrane lining.

Laboratory Testing Program

A QA testing program was established at the E&R Center to detect any gross irregularities in the lining's physical and mechanical properties and seam integrity. Because of the urgency of the installation, a sampling and testing methodology had to be developed which would produce desired results on a timely basis.

After reviewing all available test methods and inspecting the manufacturing plant, a sampling and testing program was developed. Because of the large volume of CPER sheeting, it was decided to sample every tenth production blanket out of an estimated 1000 blankets needed for the entire job. The manufacturer was required to forward to the E&R Center a sample width, 0.3 by 21 or 43 m (1 by 70 or 140 ft) (dependent on the fabrication process), including all factory seams used in the blanket. This alone amounted to approximately 929 m^2 (10 000 ft^2) of blanket samples. Each blanket sample was visually inspected and each seam in the blanket was tested by hand to initially ensure proper heat sealing.

Visual inspection of the samples included:

1. Measurement of CPE selvage for minimum specifications compliance.

2. Measurement of seam overlap to ensure specified scrim to scrim bonding.

3. Observing the overlap seam to ensure that the selvage was fully bonded to the adjacent panel.

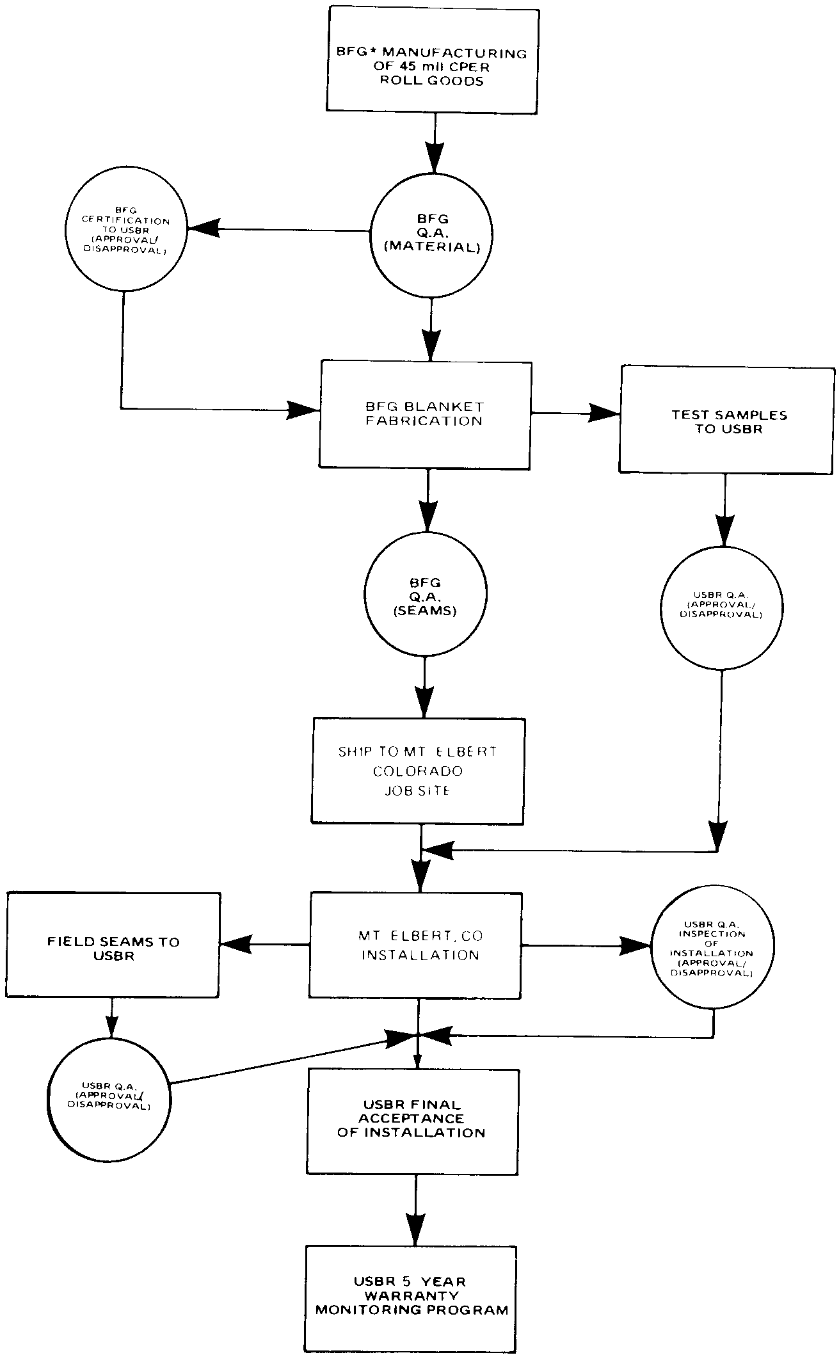
4. Observing and measuring the scrim within the CPER membrane to ensure that the scrim count was in compliance with specifications or was not too irregular.

5. Inspection for any defects such as blisters, tears, thin spots, or any other manufacturing flaws.

6. Check for exposed scrim at edge of each panel (i.e., absence of specified selvage).

After visual inspection, specimens were randomly cut from the blanket panels, environmentally conditioned, and then tested for specified physical and mechanical properties. The test properties, methods, minimum requirements, and number of specimens per blanket sample used in the laboratory QA Program are given in table 1.

The physical and mechanical properties used for evaluation of the CPER lining material were chosen after canvassing industry, searching available literature, reviewing test methods, and accomplishing some preliminary laboratory testing (table 1). The peel strength of the bonded



*BFG: BF GOODRICH COMPANY

Figure 44.—Schematic of quality assurance program for the Mt. Elbert forebay lining—manufacturing and installation.

seam (ASTM: D 1876) was an additional test property that was included to evaluate and collect data on the peeling resistance of overlapped seams, both factory and field fabricated. The breaking strength, tear strength, dimensional stability, and hydrostatic resistance tests were used in an attempt to provide methods for determining significant changes in the mechanical properties of the total membrane system. These tests were selected to evaluate the CPER as a fabric-reinforced membrane with both the polyester scrim and the CPE acting together as a system. In reality, these tests were more of an indicator of scrim strength.

The low temperature bend test was an attempt at determining changes in the CPE polymer formulation that would cause the CPE to fracture when stressed at the low specified temperature of −40 °C (−40 °F). This test was found to be a very sensitive indicator at the specified temperature and was totally dependent on correct orientation of the specimen in the test device. Also, the low temperature chamber had to be a sensitive piece of equipment that could accurately control the test temperature within ±1.1 °C (±2 °F). Coupled with IR spectral analysis, this test was intended to detect polymer composition changes.

The IR test was conducted only on the CPE sheet material without the polyester scrim. To prepare the IR specimen, one 0.5-mm (20-mil) thick CPE layer was peeled from the scrim, dissolved in an appropriate solvent, filtered, and evaporated on a NaCl crystal. The resultant IR scan was compared to an original IR scan of the correct CPE formulation in an effort to detect gross changes in the basic CPE polymer. Basically, the test shows changes in the polymer functional groups but not in the actual molecular structure. The use of a GCMS (gas chromatography-mass spectrometry) would have been more beneficial in detecting polymer change. Consequently, most of the IR scans were identical and indicated no change in basic formulation.

The ply adhesion test was chosen as a test method for determining the quality of the bond between the two 0.5-mm (20-mil) CPE sheets after laminating. Actually, the test method was an indicator for ensuring proper "strike-through" of the CPE sheet through the polyester scrim. The top and bottom sheets of CPE were essentially heat welded together through the 10 by 10, 1000-denier polyester scrim during the lamination process.

To ensure QA of the factory heat and dielectric seams, specimens were cut randomly from the blanket samples. These seams were tested for shear and peel strength in accordance with the listed ASTM test methods in table 1. The shear test essentially measured the strength of the bond between the two CPER sheets at the seam under a rapid shear loading situation such as would occur when a blanket is stressed in tension during installation.

The peel strength test was an attempt at measuring the relative bonding strength between the two CPER sheets in a peel mode of failure. Although the mode of failure may not occur in practice, the resultant peel strengths can be used as an indicator of bond. An ideal bond would fail in a ply adhesion failure mode where the CPE pulls away from the scrim rather than breaking at the seam interface. If the seam pulls apart relatively easily, this would be an indication of improper temperature and/or pressure used when fabricating the seam.

After the Mt. Elbert lining project was started, USBR field inspectors took daily cutouts of field seams that were made with the manufacturer's bodied-solvent adhesive. In addition, sample seams were made by the seaming crews, using CPER pieces and the adhesive for every 305 m (1000 ft) of field seam. The samples were sent to the E&R Center for evaluation. The major difference between factory and field seams was in the seam construction. The field seam strength relied on the thin-film adhesive system whereas, the factory seam was a more homogenous seam due to the heat or dielectric method of bonding and the absence of adhesive. Both types of seams were tested in the same manner.

Laboratory Test Results

Table 3 is a statistical summary of the physical and mechanical properties tests. The summary is based on an analysis of averages of all standard test results with the exception of low temperature and represents a total of approximately 4500 test specimens.

Ply adhesion was a fairly consistent test for analyzing the strength of the CPE strike-through within the sheet. The ply adhesion test was consistently higher than the specifications requirement of 143 kg/m (8 lb/in).

The dimensional stability test requirement (ASTM: D 1204, 1 hr at 100 °C (212 °F)) was

Table 3.—*Statistical summary of CPER physical property tests*

Physical property	Thickness	Dimensional stability Long.	Dimensional stability Trans.	Tensile breaking strength Long.	Tensile breaking strength Trans.	Tearing strength Long.	Tearing strength Trans.	Hydrostatic resistance	Ply Adhesion
	mm (in)	Percent change		N (lbf)	N (lbf)	N (lbf)	N (lbf)	MPa (lb/in²)	N/m × 10² (lbf/in)
Specification requirement	1.04 (0.041)	±2	±2	890 (200)	890 (200)	334 (75)	334 (75)	2.07 (300)	14.0 (8.0)
Mean ($\bar{X}$)	1.19 (0.047)	−0.87	+0.15	1272 (286)	1263 (284)	426 (95.8)	355 (79.8)	2.91 (422)	15.4 (8.8)
Variance $(\sigma)^2$	0.000033 (0.0000013)	0.0678	0.0052	1723.7 (387.5)	858.5 (193)	155.2 (34.9)	339.8 (76.4)	0.95 (138)	0.65 (0.37)
Standard deviation (σ)	0.0057 (0.0011)	0.26	0.072	41.50 (19.70)	29.30 (13.90)	12.45 (5.90)	18.43 (8.74)	0.97 (11.70)	0.81 (0.61)
Range	1.12 - 1.24 (0.044 - 0.049)	0.65 1.30	0 0.25	1099 - 1512 (247 - 340)	1157 - 1437 (260 - 323)	360 - 467 (81 - 105)	240 - 436 (54 - 98)	2.65 - 3.08 (385 - 446)	13.1 - 17.3 (7.5 - 9.9)

used as an indicator of uniformity as regards the degree of internal strains introduced during the manufacturing process (calendering and laminating the CPER sheet). Results from this testing showed that the material was consistently stable and well below the specifications requirement of 2 percent. The stability of the sheet was directly attributable to the polyester reinforcing scrim.

The average tensile breaking strength (ASTM: D 751, Grab method) was the same for both test directions with the statistical variability being greater for the longitudinal direction. This particular test method uses 100- by 150-mm (4- by 6-in) size specimens and 25- by 25-mm (1- by 1-in) jaws and has a tendency to "collect" or concentrate the scrim fibers in tension, thus producing fairly high tensile breaking loads. The high variability in test results generally indicates a relatively poor test method. Test results, however, proved to be consistently higher that the specifications requirements of 91 kg (200 lbs).

The tear strength test (ASTM: D 751, Method B) results were a function of the strength of individual scrim fibers in either the longitudinal (fill) or transverse (warp) direction. If all fibers accumulated during tearing, unusually high tearing strengths were produced. The longitudinal tear strength (table 4) was consistently higher than the transverse tear strength with a considerable number of transverse specimens falling below the specifications requirement of 34 kg (75 lb). Also, note that the greatest variability in test results occurred in the transverse direction. The poorest or weakest tear strength specimens all failed in a straight zippering action in which the scrim yarns broke one by one. In some instances, the tear strength was actually measuring the force required to pull the scrim yarns out from between the CPE laminated sheets, accounting for some of the variability encountered in the test data. This indicated that the 75-mm (3-in) specimen width was insufficent and that the yarn strength overcame the laminated bonding strength. In the future, tongue tear specimens will be wider in an effort to obtain a true tearing of the reinforced lining without pullout of the scrim yarns.

The hydrostatic puncture resistance test (ASTM: D 751, Method A) proved to be a fairly good indicator of the strength of the reinforced sheet. The data were fairly consistent within a single blanket panel but varied from blanket to blanket. This test may be a good aging indicator in detecting physical property change in the CPE and/or scrim. Actual test results consistently showed higher burst failures than the 2068 kPa (300 lb/in²) required by the specifications.

Numerous factory and adhesive field seams were also tested (table 4) as a QA measure. Both the hot air (Leister) and the dielectric factory seams were tested and the results indicated that the dielectric was a slightly better seam, especially since no peel failures occurred. The Leister, however, had a number of failures in peel as compared to ply. It should be noted that a ply failure is a mode of failure that exhibits delamination of the CPE from the scrim, thus proving a good bond at the seam interface. Table 4 reflects the different modes of failure and the percentages of test specimens to fail in each mode.

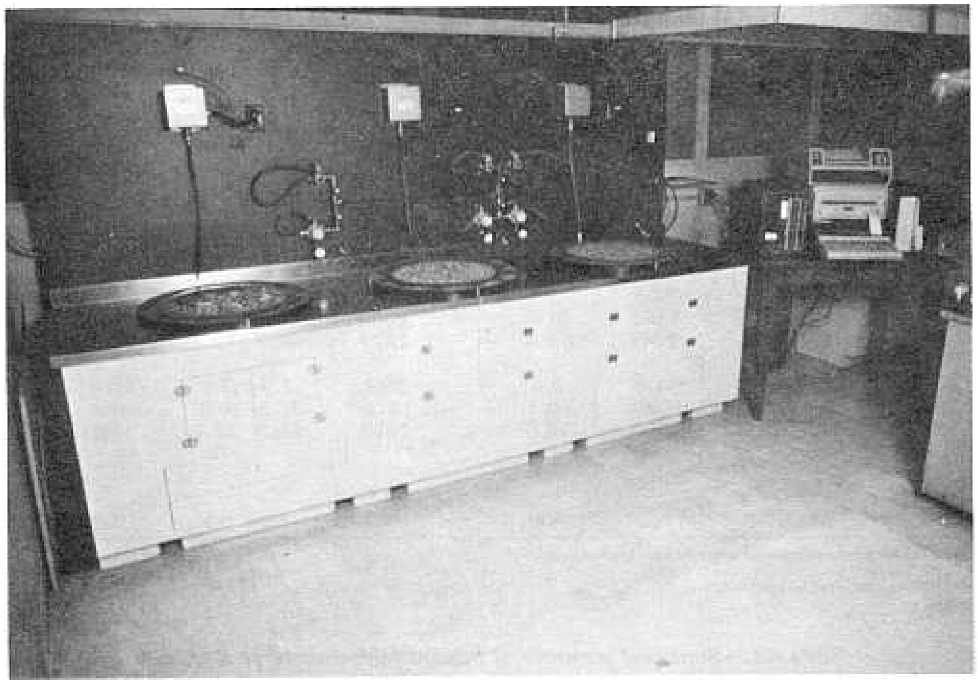


Figure 45.—Overall view of automated hydrostatic test facility with vessels (tops removed) on the left and controller on the right. Photo P-801-D-79755

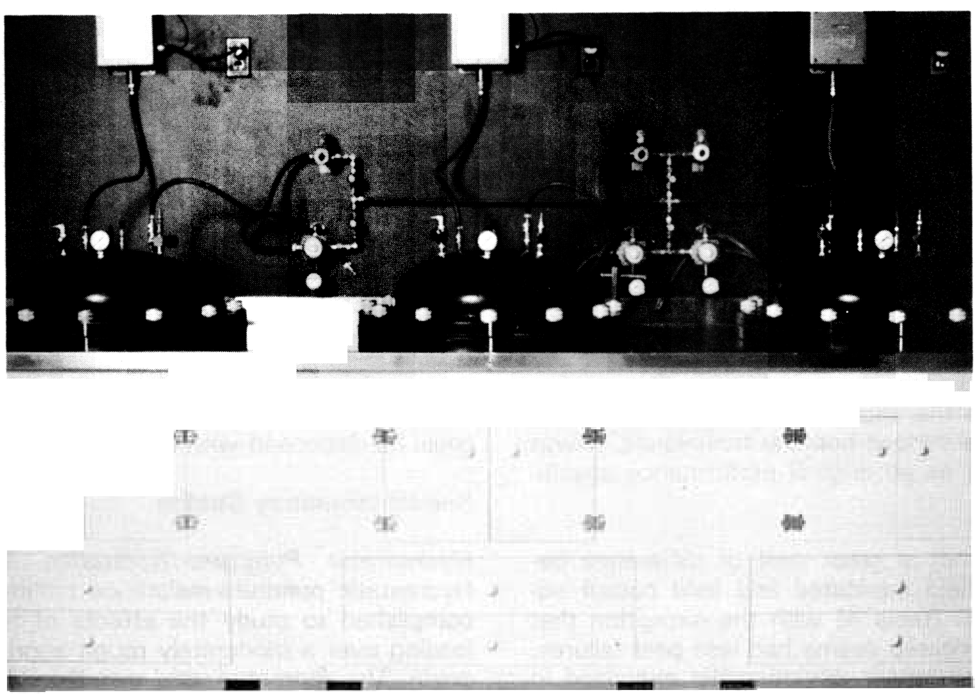


Figure 46.—Hydrostatic vessels in operation with tops in place. Photo P-801-D-79756

Table 4A. —*Statistical summary of bonded seam testing (SI units)*

Physical property	Factory seams						Adhesive field seams					
	Hot air			Dielectric			Field fabricated			Field cutout		
	Shear[1] test, N	Mode of peel test failure N/m × 10^2		Shear[1] test N	Mode of peel test failure N/m × 10^2		Shear[1] test N	Mode of peel test failure N/m × 10^2		Shear[1] test N	Mode of peel test failure N/m × 10^2	
		Ply	Peel		Ply	Peel		Ply	Peel		Ply	Peel
Specifications requirement	890	—	—	890	—	—	890	—	—	890	—	—
Mean ($\bar{X}$)	1190	55.0	26.4	1293	67.4	—	1350	55.9	20.5	1412	53.8	20.1
Variance $(\sigma)^2$	3905	13.4	27.8	2641	13.4	—	1277	56.7	15.2	3067	53.4	11.6
Standard deviation (σ)	62.5	3.7	5.3	51.4	3.4	—	35.7	7.5	3.9	55.4	7.3	3.4
Range	890-1370	46.4-68.1	15.8-35.0	1000-1406	60.1-75.0	—	1219-1695	37.3-89.3	10.9-27.5	1104-1580	38.4-83.7	12.8-26.6
Mode of failure: Percent of total	100	66	34	100	100	—	100	88	12	100	73	27

[1]The specifications require that the parent material break before the seam fails in shear

Note: There was no specifications requirement for peel testing

Table 4B. —*Statistical summary of bonded seam testing (in-lb units)*

Physical property	Factory seams						Adhesive field seams					
	Hot air			Dielectric			Field fabricated			Field cutout		
	Shear[1] test, lbf	Mode of peel test failure lbf/in		Shear[1] test lbf	Mode of peel test failure lbf/in		Shear[1] test lbf	Mode of peel test failure lbf/in		Shear[1] test lbf	Mode of peel test failure lbf/in	
		Ply	Peel		Ply	Peel		Ply	Peel		Ply	Peel
Specifications requirement	200	—	—	200	—	—	200	—	—	200	—	—
Mean ($\bar{X}$)	267.5	31.4	15.1	290.6	38.5	—	303.5	31.9	11.7	317.4	30.7	11.5
Variance $(\sigma)^2$	877.9	7.68	15.9	593.8	7.67	—	287.1	32.4	8.7	689.6	30.5	6.6
Standard deviation (σ)	29.6	2.77	4.0	24.4	2.76	—	16.9	5.7	2.95	26.3	5.5	2.56
Range	200-308	26.5-38.9	9-20	225-316	34.3-43.8	—	274-381	21.3-51	6.2-15.7	248.2-355	21.9-47.8	7.3-15.2
Mode of failure: Percent of total	100	66	34	100	100	—	100	88	12	100	73	27

[1]The specifications require that the parent material break before the seam fails in shear

Note: There was no specifications requirement for peel testing

The peel test was performed in an effort to further analyze the seam strengths and modes of failure of the various bonding techniques. It was not included as an original performance specification.

There was not a great deal of difference between the field fabricated and field cutout adhesive seams (table 4) with the exception that the field fabricated seams had less peel failures. This reflected better workmanship exercised in preparing a sample that was intended to be used for test purposes. The conclusion was that the field cutout samples reflected the actual situation, and the separately fabricated samples could be dispensed with in future work.

Special Laboratory Studies

Hydrostatic Puncture-Resistance Testing. — Hydrostatic puncture-resistance testing was accomplished to study the effects of hydrostatic loading over a moderately rough aggregate subgrade. The apparatus used was the "Automated Hydrostatic Test Facility" recently developed at the USBR laboratories [5]. The vessels (figs. 45

and 46) are 0.61 m (24 in) in diameter and are capable of testing lining materials over any subgrade and under variable hydrostatic or hydrodynamic loading conditions.

Two 1.14 mm (45-mil) CPER lining samples were subjected to 2 months of static water pressure testing. One sample incorporated a factory Leister seam and the other an adhesive field seam. Both were tested over a 10- to 12-mm (3/8- to 1/2-in) aggregate subgrade at a hydrostatic head of 21 m (70 ft) for 1 month and 43 m (140 ft) during the second month. The pressure was raised incrementally at a slow rate to simulate the filling of the Mt. Elbert Forebay. See figure 47 for the resultant deformation of the CPER.

Although the sheet material did not physically fail in this short-term test, several observations on its performance were noted:

1. The CPER sheet conformed to the aggregate subgrade within the elongation limitations of the sheet.

2. Sharp, angular aggregate tended to separate the CPE from the scrim grid, and the CPE deformed over the rock.

3. The subgrade under the field seam was noticeably moist but no apparent rupture within the membrane or seam was evident. The subgrade under the factory seam was dry.

4. The CPE had a tendency to flow into the grid pattern of the scrim (fig. 47) causing a pronounced wafflelike texture. This occurred over voids in the aggregate subgrade that were bridged by the CPER sheet. This test observation reinforced the concern about loose aggregate on a relatively hard subgrade surface and the possibility of the CPER bridging void areas.

Solids Content (CPE Resin) of the Bodied-Solvent Adhesive.—To check the consistency of the bodied-solvent adhesive used in making the field seams, samples were taken in the field and tested for solids content at the E&R Center laboratories. The samples were taken initially from the supply drums of adhesive and then from individual application buckets used by the field seaming crews. The bucket samples were taken after the crews had been working, and the adhesive was very low in each bucket. The samples from the supply drums show a 9.4-percent solids content (CPE resin); whereas, the average of the used buckets showed an 11.2-percent solids content. This was not considered a significant change in adhesive consistency and would in no way affect seam integrity.

RESEARCH STUDIES

General

Included in the specifications for this work is a 5-year maintenance warranty period on the membrane lining. To monitor the performance of the lining during the warranty period and for long-term research purposes, a special field test section was installed in the forebay reservoir. In conjunction with the field study, laboratory studies will be performed. Also, a continuous "state-of-the-art" literature survey is being conducted on flexible membrane linings. Reference [6] summarizes the initial survey. Quarterly reports will be made updating the "state-of-the-art" survey.

Special Field Test Section

On August 14, 1980, a 6- by 30-m (20- by 100-ft) test section was installed in the southwest corner of the reservoir. This location (at elevation 2936 m (9633 ft)) was selected to allow easy retrieval of the samples over a period of years. The test section is within the 9-m (30-ft) water-level fluctuation of the reservoir and on a relatively flat beaching slope of 20:1. The test lining was placed on a 50-mm (2-in) cushion of sand above and separate from the main lining, thus precluding the need to cut and patch the actual lining to obtain samples.

The limitations of the test section are that the reservoir water will have access to both sides of the test membrane, and the effects of stresses introduced into the actual reservoir lining during installation and operation will not be reflected except for freeze-thaw cycling. Also, the effects of hydrostatic pressure present in deep parts of the reservoir will not be evident.

As the lining placement progressed, some unanticipated questions arose and the original test section plan was modified slightly. In particular,

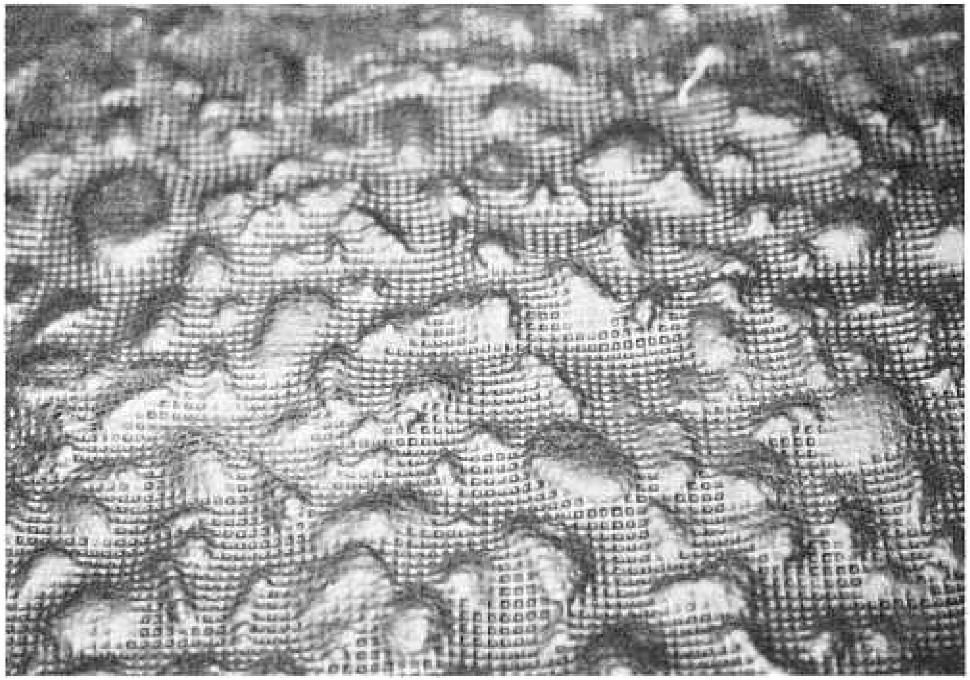


Figure 47.—Resultant deformation of CPER after testing over an aggregate subgrade in the hydrostatic vessels. Photo P-801-D-79757

it was decided to compare all three types of seams (hot-air, dielectric, and bodied-solvent adhesive), as well as capped versus uncapped field seams. Also, anticipating a potential problem of water wicking within the polyester scrim, it was decided to test coated edges versus noncoated edges in an effort to detect any noticeable physical property changes. The long edges of each panel section were protected from wicking by coating them with the bodied-solvent adhesive.

All test section work was performed by the installer in accordance with USBR instructions and with the USBR inspectors present. The contractor's installation supervisor and a three-man seaming crew fabricated the test section using standard field installation procedures. The following is a summary of the fabrication and installation procedures:

1. Sample blanket sections representing each of the two factory seaming methods (dielectric and Leister (hot-air)) were taken from blankets already on the job. Each sample blanket section measured approximately 17 by 3.5 m (55 by 12 ft).

2. A 0.61- by 17-m (2- by 55-ft) section was cut from each of the above samples and returned to the E&R Center in Denver for initial physical property testing.

3. The two sample sections (each approximately 3 by 17 m (10 by 55 ft)) were seamed together using standard field seaming procedures as specified except that the 75-mm (3-in) cap strip was omitted. The two sections were first positioned such that the factory seams of each were offset a minimum of 0.15 m (6 in).

4. After field seaming the sample sections together, both sections were cut across the factory seams and a minimum of 1.5 m (5 ft) from either end. The cut sections were then field seamed back together using standard seaming procedures with a cap strip.

5. The 17- by 6-m (55- by 20-ft) test section was cut into 11 individual panels, each measuring approximately 1.5 m (5 ft) in width by 6 m (20 ft) in length. The two long edges of each panel section were coated with the

bodied-solvent adhesive and the two short edges were left as cut edges.

Each panel thus contains one 3-m (10-ft) dielectric seam, one 3-m (10-ft) Leister hot-air seam, one 2.7 m (9 ft) of capped, bodied-solvent adhesive seam, one 1.5 m (5 ft) of uncapped bodied-solvent adhesive seam, and a minimum of 7.4 m^2 (80 ft^2) of CPER lining material.

6. The 11 test panels were placed on a 50-mm (2-in) sand bed over the installed CPER lining (fig. 48). The panels were positioned approximately 1.5 m (5 ft) apart starting with panel No. 1 at the south end of the test section location.

7. The area of the test panels was covered with the specified protective earth materials.

The sampling program for the test panels will begin with panel No. 1 in the spring of 1981. After 1 year of service (October 1981), panel No. 2 will be taken and panels No. 3 through 11 will be taken on a yearly basis thereafter. If, after 5 years, there is little significant change in physical properties, the sampling program may be changed to one sample panel every 2 or more years until all panels have been removed.

Listed below are the physical and mechanical property tests which will be conducted on the field samples to determine changes in the CPER sheet material and the various types of seams used in the lining installation.

1. CPER sheet material tests:

   a. Hydrostatic resistance using the Mullen Burst (ASTM: D 751-79, Method A)

   b. Hydrostatic puncture resistance using the USBR test facility [4]

   c. Ply adhesion (ASTM: D 413-76, Machine Method, type A)

   d. Tear resistance using the tongue tear (ASTM: D 751, Tongue Tear, Method B) or other approved tear test method

   e. Low temperature bend tests using a ⅛ mandrel (ASTM: D 2136-78) or other approved test method

2. CPER seam tests:

   a. Seam strength in peel (ASTM: D 1876-78)

   b. Static mass seam strength in shear (nonstandard)

   c. Visual inspection

The wicking phenomenon associated with the polyester scrim will be examined by comparing sections of the test panel that have exposed (cut) scrim edges with those that are coated with bodied-solvent adhesive. In addition, a differential scanning calorimeter and/or a gas chromatograph-mass spectrometer will be used in an effort to detect any radical changes in the polymer over time.

Laboratory Studies

Long-term water immersion tests were started November 21, 1980, on retained samples of the CPER membrane lining and seams. These samples are being subjected to Denver running tapwater 10 to 16 °C (50 to 60 °F). The samples will be removed and tested after the following intervals: 13, 26, 52, 78, 104, 156, 208, and 260 weeks. The following laboratory tests will be conducted to monitor changes in the membrane lining.

- Weight determinations (surface dry and after conditioning)
- Tear resistance (ASTM: D 751-79, Tongue Tear, Method B)
- Low temperature bend (ASTM: D 2136-78)
- Ply adhesion (ASTM: D 413-76, Machine Method, Type A)
- Hydrostatic resistance (ASTM: D 751-79, Method A, Mullen Burst)
- Seam strength in shear (ASTM: D 751-79, modified)
- Seam strength in peel (ASTM: D 1876-78)

Freeze-thaw tests will also be conducted on samples of the membrane lining.

Figure 48.—Installing CPER test panels over sand bedding in field test section. Photo P-801-D-79758

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Note: From November 1979 to May 1981, the Bureau of Reclamation was known as the Water and Power Resources Service; consider the names synonymous in this Bibliography.